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Particulate Sampling and Analysis

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16. ABSTRACT The chapter provides information needed to ensure that sampling and data analysis are well done. It discusses sampling and analysis associated with mass tests using EPA Test Methods 5 and 17 and particle size distribution tests conducted with cascade impactors. All steps in the sampling and data analysis process are covered. Considerably more space is given to cascade impactors than to EPA Test Method 5, mainly because cascade impactors are more difficult to use and data reduction is difficult. Computer programs for reducing mass train and cascade impactor data are presented, along with quality control recommendations.

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a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
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Flue Gases	Data Reduction	Stationary Sources	21B	09B
Sampling	Quality Control	Particulate	14B	13H, 14D
Analyzing		Cascade Impactors		
Particles			14G	
Dust			11G	

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CHAPTER 31

PARTICULATE SAMPLING AND ANALYSIS

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1 INTRODUCTION

There are several reasons for sampling particulate matter from smoke stacks. Among the most common of these are sampling to determine compliance with air pollution regulations, sampling to determine whether or not a particulate control device meets design requirements, sampling to develop emission factors, sampling to provide trouble shooting information, and sampling to develop a data base for future reference. In many of these cases large amounts of money depend on the outcome. If the emissions exceed the allowable limit, a plant may be fined, shut down, or forced to operate at reduced capacity. If a device fails to meet design requirements, the vendor may be liable for considerable dollar amounts. Therefore, it is extremely important that the sampling and data analysis that follows the sampling effort be well done.

High-quality particulate data are very difficult to obtain—both because the sampling methods generally leave something to be desired and because the conditions that exist in typical industrial situations are not the best in the world. In spite of these problems, good high-quality data can be obtained if sufficient care is taken. The general requirement is that the same care must be taken as would be taken in an analytical laboratory. This means that all equipment must be calibrated, all procedures written down and checked, and a good quality assurance program be in place. It also means that the people involved in particulate sampling must be well trained and well supervised. Given the stakes that are riding on particulate data, all of these requirements should be insisted upon by anyone who needs or uses particulate data.

The purpose of this chapter is to provide information needed to ensure that the sampling and data analysis are indeed well done. The emphasis of the discussion will be on sampling and analysis associated with mass tests using EPA Test Method 5 and EPA Test Method 17 and particle size distribution tests conducted with cascade impactors. All steps in the sampling and data analysis process will be covered. Considerably more space will be given to cascade impactors than to EPA Test Method 5, mainly because cascade impactors are more difficult to use and data reduction is difficult. Computer programs for reducing mass train and cascade impactor data are presented along with quality control recommendations.

2 STEPS IN PARTICULATE SAMPLING

All of the common particulate measurement techniques, for both total mass and mass as a function of particle diameter, are extractive techniques. This means that a representative sample of the aerosol being sampled must be withdrawn from the bulk aerosol flow and transported to the measuring device. The measurement device actually only separates the particles from the gas. Final measurement is done by weighing the captured particulate matter on a suitable balance.

An overview of the steps required for particulate sampling is given in Table 1. Note that each of these steps must be carried out with extreme care.

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Table 1 Steps in Particulate Sampling

1. Gas velocity and composition determination
2. Sample extraction
3. Sample transport
4. Sample collection
5. Sample analysis
6. Data reduction and data analysis

Note that although information on particle mass concentration is desired, the gas flow rate, gas velocity profile, and the composition of the major components of the flue gas stream must be determined first.

3 VELOCITY AND VOLUMETRIC FLOW RATE

Gas velocity and volumetric flow rate are determined by using EPA Method 1 and EPA Method 2.[1] EPA Method 1 specifies the number and location of traverse points and EPA Method 2 specifies the way to make the measurement. An S-type pitot tube is used to make the measurement. The equipment used to make the measurement is shown in Figure 1.

In a traverse the duct or stack is divided into a number of equal areas. The traverse point is located in the center of each area. The sampling site should be located at least eight stack or duct diameters downstream and two diameters upstream from a flow disturbance. If such a site is not available, a location at least two duct diameters downstream and half a diameter upstream from a disturbance may be selected. For a rectangular duct the equivalent diameter D_e should be used.

$$D_e = \frac{2LW}{L + W} \tag{1}$$

L and W are the dimensions of the two sides of the rectangular duct.

The number of traverse points is a function of both the duct diameter and the sampling location. Figure 2 can be used to determine the number of traverse points necessary for a mass sample. Figures 3 and 4 show how the duct should be divided. To use the figure determine the number of duct diameters upstream and downstream from a flow disturbance. Determine the minimum number of traverse points for each case from Figure 2. Select the higher of the two, or a greater value, so that for circular ducts the number of traverse points is a multiple of 4 and for rectangular ducts it is one of the numbers given by Table 2. The location of the traverse points for circular ducts is given in Table 3.

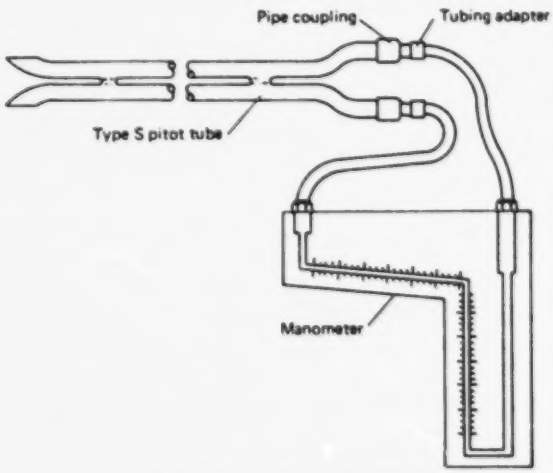


Fig. 1 Pitot tube manometer assembly.[1]

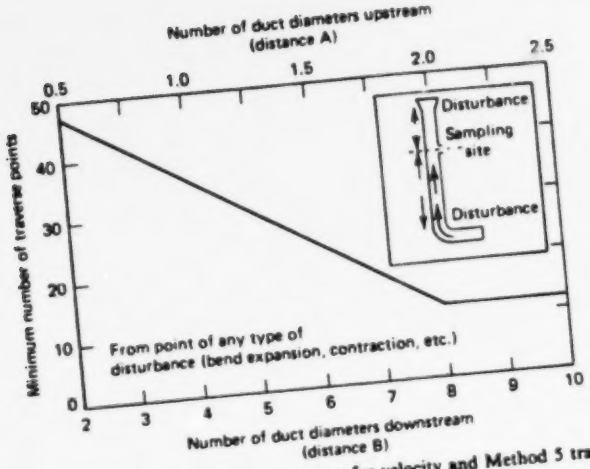


Fig. 2 Minimum number of traverse points for velocity and Method 5 traverse.[1]

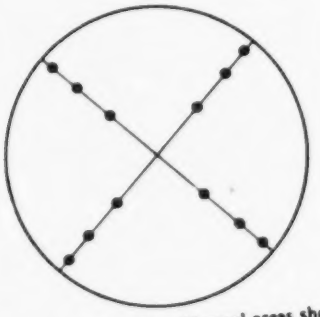


Fig. 3 Cross section of circular stack divided into 12 equal areas showing location of traverse points at centroid of each area.

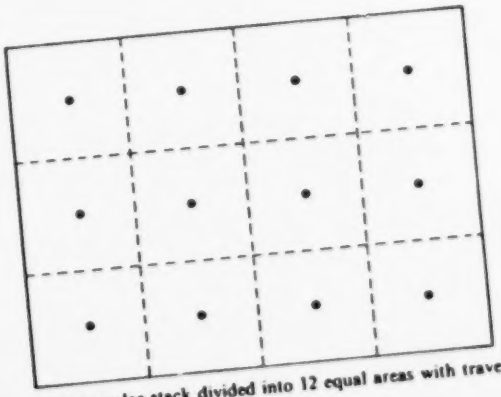


Fig. 4 Cross section of rectangular stack divided into 12 equal areas with traverse points at centroid of each area.

Table 2 Cross-Sectional Layout for Rectangular Stacks[1]

No. Traverse Points	Matrix Layout
9	3 × 3
12	4 × 3
16	4 × 4
20	5 × 4
25	5 × 5
30	6 × 5
36	6 × 6
42	7 × 6
49	7 × 7

Velocity measurements should be conducted at each of the traverse points using the procedures given in EPA Method 2. The data should be recorded on a form such as that shown in Figure 5.

EPA Method 2 also gives details on equipment calibration which is necessary for high quality measurement.

The stack velocity V_s is calculated from

$$V_s = k_p C_p \, [(\Delta p)^{0.5}]_{av} \left(\frac{T_s}{P_s M_s}\right)^{0.5} \tag{2}$$

where k_p is the pitot tube constant = 34.97 m/s g/g-mole (mm Hg)/°K(mm H_2O), C_p is the pitot tube coefficient, $[(\Delta p)^{0.5}]_{av}$ is the average square root of the velocity head in the stack which is not

Table 3 Location of Traverse Points in Circular Stacks (Percent of Stack Diameter from Inside Wall to Traverse Point)

Traverse Point Number on a Diameter	Number of Traverse Points on a Diameter											
	2	4	6	8	10	12	14	16	18	20	22	24
1	14.6	6.7	4.4	3.3	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.1
2	85.4	25.0	14.7	10.5	8.2	6.7	5.7	4.9	4.4	3.9	3.5	3.2
3		75.0	29.5	19.4	14.6	11.8	9.9	8.5	7.5	6.7	6.0	5.5
4		93.3	70.5	32.3	22.6	17.7	14.6	12.5	10.9	9.7	8.7	7.9
5			85.3	67.7	34.2	25.0	20.1	16.9	14.6	12.9	11.6	10.5
6			95.6	80.6	65.8	35.5	26.9	22.0	18.8	16.5	14.6	13.2
7				89.5	77.4	64.5	36.6	28.3	23.6	20.4	18.0	16.1
8				96.7	85.4	75.0	63.4	37.5	29.6	25.0	21.8	19.4
9					91.8	82.3	73.1	62.5	38.2	30.6	26.1	23.0
10					97.5	88.2	79.9	71.7	61.8	38.8	31.5	27.2
11						93.3	85.4	78.0	70.4	61.2	39.3	32.3
12						97.9	90.1	83.1	76.4	69.4	60.7	39.8
13							94.3	87.5	81.2	75.0	68.5	60.2
14							98.2	91.5	85.4	79.6	73.9	67.7
15								95.1	89.1	83.5	78.2	72.8
16								98.4	92.5	87.1	82.0	77.0
17									95.6	90.3	85.4	80.6
18									98.6	93.3	88.4	83.9
19										96.1	91.3	86.8
20										98.7	94.0	89.5
21											96.5	92.1
22											98.9	94.5
23												96.8
24												98.9

Plant _____
Date _____
Run no. _____
Stack Diameter, in. _____
Barometric Pressure, in. Hg _____
Static pressure in stack (P_g), in. Hg _____
Operators _____

Schematic of stack cross section

Traverse point number	Velocity head, in. H_2O	$\sqrt{\Delta_p}$	Stack temperature (T_s), °F
	Average		

Fig. 5 Form for recording velocity traverse data.[1]

the same as the square root of the average velocity head in the stack, T_s is the absolute temperature of the gas, P_s is the pressure in the stack, and M_s is the molecular weight of the stack gas. A computer program to do the calculations is presented later.

The volumetric flow rate determined by Method 2 is usually within ±10% of the true flow rate.

4 GAS COMPOSITION

EPA Test Method 3[1] is used to determine the dry molecular weight of the gas being sampled and the CO_2 and O_2 concentrations of the gas. The measurement is made using an Orsat analyzer. The Orsat analyzer is used to determine the CO_2, CO, and O_2 with N_2 determined by difference in a stack gas. If the stack gas is likely to contain other gases, then steps must be taken to ensure that the concentrations of the major gases are measured.

The operation of the Orsat analyzer is fully explained in the manufacturer's instructions which should be carefully followed.

5 SAMPLE REMOVAL

The first step in the sampling process is obtaining a representative sample of the aerosol being sampled. If this step is not carried out properly, the data will be of poor quality regardless of how well the rest of the sampling is done.

The major factors that make it difficult to obtain a representative sample are:

1. Stratification of the gas flow and/or stratification of the particulate matter in the gas.
2. Misalignment of the probe so that it is not parallel to the velocity of the bulk gas flow.
3. Failure to sample at the isokinetic sampling rate.

With proper sampling procedures, all of these difficulties can be dealt with.

5.1 Stratification

Stratification is handled by sampling at many points in the gas. The procedures for carrying out this multipoint sampling are straightforward when mass emission data are needed. With a mass train, such as the EPA Test Method 5 train, this multipoint sampling is handled by traversing the duct and sampling for specified times at each of the traverse points. As will be discussed later, such traversing is impossible with cascade impactors. Thus multipoint sampling means that single impactor runs must be conducted at each of the traverse points.

The number of traverse points depends on the location of the sampling location. The nearer the sampling point is to a flow disturbance, the more traverse points are required. For mass sampling the number and location of the sampling points are the same as the number and location of the velocity traverse points discussed in Section 3.

Ideally, the same number of sampling points as required for mass sampling should also be used for cascade impactor sampling. However, as is discussed in the section on impactors, traversing a cascade impactor is generally impossible if isokinetic sampling is to be maintained. This means that multipoint sampling with cascade impactors involves a complete cascade impactor run at each of the sampling points. A large number of traverse points would require a large number of complete cascade impactor runs. Such a large number of samples would be impossible to obtain. Thus for cascade impactor sampling a compromise needs to be made. In most cases cascade impactor sampling is done at one or two representative locations in the duct. This inability to traverse a cascade impactor train is one of the major reasons that mass concentrations measured by cascade impactor do not agree with mass concentrations measured by EPA Test Method 5.

Note that the above procedure takes care of problems due to gas flow stratification or nonuniformity. It does not take care of problems that may be caused by particle stratification. Because particles have inertia, and the larger particles have more than the smaller particles, particles can become stratified even if the gas flow is good. Such stratification should be checked for and an appropriate sampling strategy worked out if particle stratification exists.

The problem is especially serious if particle size data are desired for particles larger than 5–10 μm in diameter. Particles larger than this are likely to be adversely affected by flow disturbances, whereas smaller particles will not be affected. Thus the particle size distribution can be quite accurate for the smaller diameter particles and totally wrong for the larger diameter ones.

The stratification problem is especially serious if a full traverse is impossible. Some idea of the possible errors introduced by stratification and single point sampling can be obtained from Table 4.

Table 4 Comparison of Mass Determined with Single-Point Impactor Measurement with Full Traverse Mass Train[3]

Plant	Run No.	C_i/C_m
1	1	7.11
	2	2.56
	3	2.27
	4	0.74
	5	0.94
	6	0.95
	7	1.31
2	1	0.66
	2	0.63
	3	0.57
3	1	0.62
	2	0.81
	3	0.50
4	1	0.94
	2	0.55
	3	0.52
	4	0.50

Note that the data were obtained by two different methods, cascade impactors and mass trains, so some of the differences may be due to method differences and not stratification.

Brooks[3] has estimated the error due to stratification is on the order of −40% to +60% at the inlet of a particulate control device and −60% to +150% at the outlet of a particulate control device. The only way to reduce this error is by multipoint sampling.

5.2 Isokinetic Sampling

If the gas velocity in the sampling probe is not the same as the gas velocity in the bulk gas, the flow streamlines will be distorted. Because particles have finite size and mass, they will not completely follow the distorted flow streamlines caused by the velocity mismatch. Thus, sampling errors will result because of the velocity mismatch. Figure 6 shows the flow streamlines and the particle trajectories for the three cases of matched velocity, sampling velocity greater than the gas velocity, and sampling velocity less than the gas velocity.

The sampling velocity that matches the gas velocity is called the isokinetic velocity and the sampling flow rate that is achieved with the isokinetic velocity is the isokinetic sampling rate. In order to sample at the isokinetic rate the sampling volumetric flow rate and probe nozzle diameter must be carefully selected.

The sampling nozzle that will give the isokinetic sampling rate for given gas flow may be found from Figure 7.

The errors due to nonisokinetic sampling are a strong function of particle diameter. Stairmand[4] reported the data shown in Table 5. Note that the error due to nonisokinetic sampling becomes small for the 1-μm diameter particles.

Davies[5] reported that the following equation can be used to estimate the error due to nonisokinetic sampling with sharp-edged probes.

$$\frac{C_s}{C_a} = \frac{V_a}{V_s} - \frac{0.5(V_a/V_s - 1)}{K_\rho + 0.5} \tag{3}$$

where C_s is the sampled concentration, C_a is the actual concentration, V_a is the actual velocity, V_s is the sample velocity, and K_ρ is the inertial impaction parameter.

$$K_\rho = \frac{d_p^2\, \rho\, V_a C}{9\mu D} \tag{4}$$

where d_p is the particle diameter, ρ is the particle density, μ is the gas viscosity, D is the orifice diameter, and C is the Cunningham correction factor.

Figure 8 is a plot of Eq. (3) for the indicated conditions of gas velocity and particle diameter. Again note that for particles with diameters less than about 5 μm, the error due to nonisokinetic sampling is acceptably small.

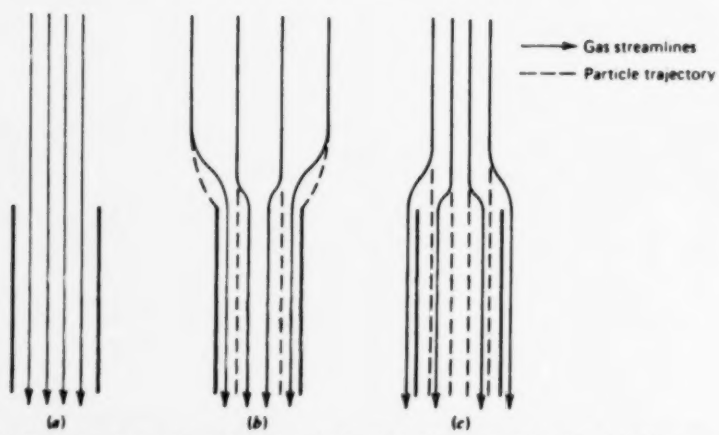


Fig. 6 Gas streamlines and particle trajectories for (a) isokinetic sampling, (b) subisokinetic sampling, and (c) superisokinetic sampling.

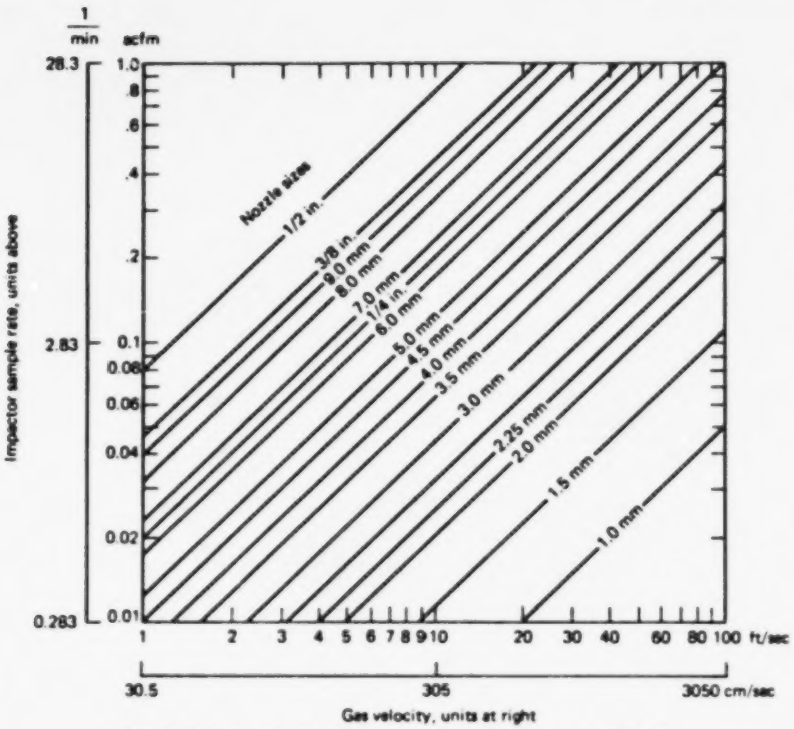


Fig. 7 Nomograph for selecting nozzles for isokinetic sampling.[14]

When the duct is traversed, it is necessary to adjust the sampling rate to maintain isokinetic sampling. This means that the gas velocity at the sampling location must be measured. The EPA Test Method 5 train has a pitot tube located at the sampling point so the operator knows at all times what the gas velocity is. Other sampling trains do not have a pitot tube so the gas velocity at each of the sampling points must be determined with a separate velocity traverse, for example, using EPA Test Method 2.

One should note that all of the discussion of isokinetic sampling and all of the experiments are based on sampling in laminar or very low turbulence flows. This is not the situation that exists in industrial installations. In most industrial situations the flow is highly turbulent. The velocity component parallel to the sampling nozzle can be expected to fluctuate over about ±10% with similar variations in the angle of the flow with respect to the nozzle.

This means that isokinetic sampling in most situations is an averaging process. In all cases the flow turbulence will be large with respect to the sampling nozzle. So in a turbulent gas flow isokinetic sampling can only be approximated.

Table 5 Effects of Nonisokinetic Sampling[4]

Particle Diameter, μm	V_n/V_s	C_s/C_n
100	2	1.99
10	2	1.54
1	2	1.013
100	0.67	0.67
10	0.67	0.82
1	0.67	0.996

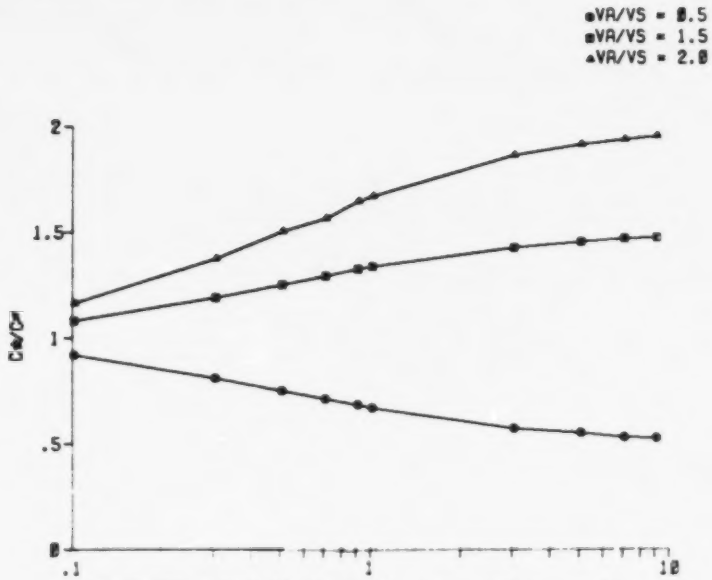


Fig. 8 Effect of anisokinetic sampling on measured concentration.

With the EPA Test Method 5 train the sampling velocity is set to match the stream velocity as measured by a pitot tube. Brooks[3] has shown that for this mode of operation:

> *Particle mass emission errors at a point will not be larger than the errors in the measured stream velocity as long as the sample velocity is maintained equal to the measured velocity and the sampling probe is properly aligned with the stream.*

Note that this statement is for mass measurements at a single point.

5.3 Probe Alignment

Probe misalignment can be a serious problem. Even under isokinetic conditions the measured concentration will be less than the true concentration. Figure 9 shows the effect of probe misalignment on the measured concentration for several conditions. Probe misalignment is not a serious problem if the probe is aligned within 5° of the true gas velocity.

Probe misalignment and failure to sample at or near the isokinetic sample rate are operator errors. These problems are best handled by careful instruction of the sampling personnel. The leader of the sampling team must be sure that everyone in the team understands the need for care. In this way errors due to anisokinetic sampling and probe misalignment can be avoided.

In the final analysis, the error introduced by sample extraction can be held to less than a normalized standard deviation of 5% of the total mass if proper care is taken.

6 SAMPLE TRANSPORT

As soon as the sample is extracted from the gas flow, it must be transported through the sampling probe to the collector. In some sampling trains the distance between the sampling nozzle and the collector is fairly short so probe losses are minimized. In other trains, such as the EPA Test Method 5, the distance between the nozzle and the collector can be very long. In such cases probe losses can be high.

The probe loss problem depends on the sampling method used. If an instack filter or impactor is used, the sample line loss is minimal. However, if an external filter or impactor is used, the sample line loss can become large.

If the measurement is for total mass, sample line loss is not too serious a problem if the sample line is carefully cleaned and if the material contained in the sample line catch is included in the

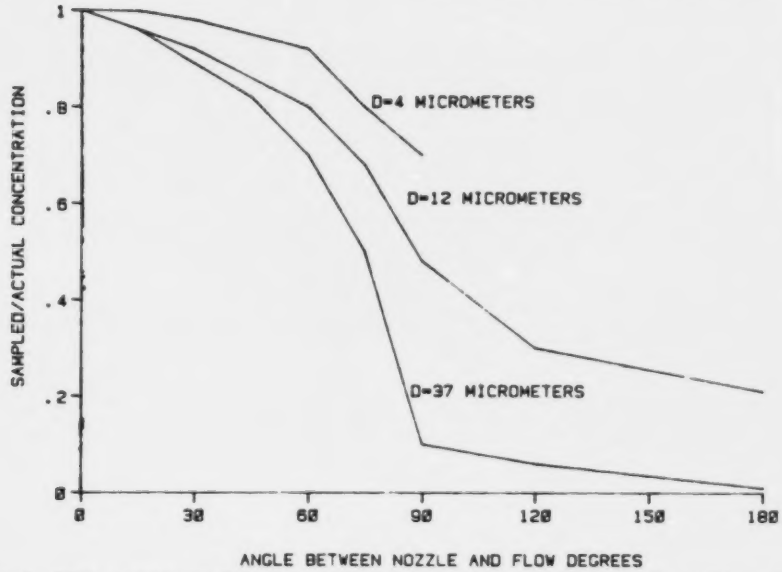


Fig. 9 Effect of probe misalignment on measured concentration under isokinetic conditions after Fuchs.[29]

total mass catch. However, as can be seen from Figure 10, if the particle size distribution data are desired, probe losses can distort the measured size distribution, especially for particles with diameters greater than 10 μm.

7 MASS SAMPLING

Sampling to determine particle mass concentration is generally required to determine compliance with air pollution regulations. Such sampling must follow procedures specified by the air pollution regulations. Failure to follow the specified procedures can invalidate the entire test.

There are two basic mass sampling techniques—one uses an instack filter to capture the particles (EPA Method 17 is an example) and the other uses an out-of-stack filter in a heated filter holder (EPA Method 5 is an example). The two methods may or may not give the same result. Particulate matter is defined by the sampling method and the temperature at which the particles are collected. Thus if the instack and out-of-stack filters are at different temperatures, they may not see the same material as particles. For example, in many combustion sources there are significant quantities of sulfuric acid. If the filter is maintained at a low temperature, the sulfuric acid will condense and be captured as particles. On the other hand, if the filter is maintained at a high temperature, the sulfuric acid will not condense and any sulfuric acid particles formed in the stack will be evaporated. The concentration of particulate matter measured at the two temperatures will be very different.

The choice of which method should be used is given in the air pollution regulations. The two EPA approved sampling methods, EPA Method 5 and EPA Method 17, are discussed below.

7.1 EPA Test Method 5

Particulate testing for determination of compliance with EPA mass emission standards must usually be conducted with EPA Test Method 5, "Determination of Particulate Emissions from Stationary Sources."[1] The exact procedures that must be followed for EPA Test Method 5 are described in the appropriate air pollution regulations. Most states also require some form of the EPA Method 5 train for compliance testing.

Note that with EPA Method 5 particulate matter is defined as whatever is captured in the probe and the filter (the so-called front half of the train). Because the filter is maintained at a temperature different from the temperature of the stack, material that is caught on the filter may or may not exist as particulate matter in the stack. This is a major conceptual difference between Method 5 and EPA Method 17 which uses an instack filter.

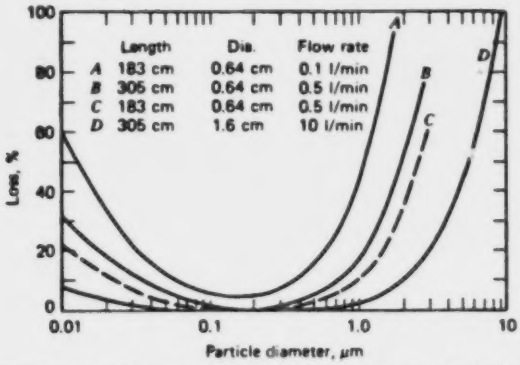


Fig. 10 Probe losses due to settling and diffusion for spherical particles having a density of 2.5 g/cm³ under laminar flow.[3]

With the EPA Method 5 train an isokinetic sample is removed from the duct at specified traverse points. The idea is to obtain an integrated mass sample over the cross section of the duct. The location and number of traverse points is discussed in Section 3 and depends on the location of the sampling ports relative to flow disturbances.

7.1.1 *Description of Sampling Train*

The design specifications of the particulate sampling train used by EPA (see Figure 11) are described in APTD-0581. Commercial models of this train are available. A brief discussion of the train follows. The nozzle is made of stainless steel (316) with sharp tapered leading edge. The probe is Pyrex glass with a heating system capable of maintaining a minimum gas temperature of 120°C at the exit end

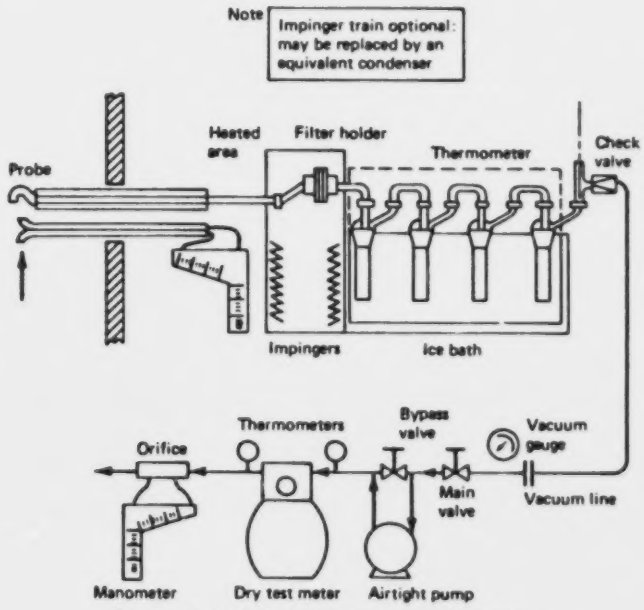


Fig. 11 EPA Method 5 particulate sampling train.

Table 6 Sources of EPA Method 5 Particulate Sampling Equipment

Company	Address
Aerotherm-Acurex	485 Clyde Avenue Mountain View, CA 94042
Andersen Samplers, Inc.	4215 Wendell Drive Atlanta, GA 30336
Joy Manufacturing Co.	Commerce Road Montgomeryville, PA 18936
Lear Siegler, Inc., Environmental Technology Division	One Inverness Dr. East Englewood, CO 80110
Misco International Chemicals, Inc.	1021 S. Noel Avenue Wheeling, IL 60090
RCA, Inc., Div. Andersen Samplers, Inc.	See address above
Scientific Glass and Instruments, Inc.	7246 Wynnewood Houston, TX 77001

during sampling to prevent condensation from occurring. When length limitations (greater than about 3 m) are encountered at temperatures less than 315°C, Incoloy 825 or equivalent may be used. Probes for sampling gas streams at temperature in excess of 315°C must have been approved by the administrator prior to their use.

A type S pitot tube or equivalent is attached to the probe to monitor stack gas flow rate. A Pyrex filter holder is used. The filter holder is in a heated box.

The filter is fiberglass and should be at least 99.7% efficient for 0.3 μm diameter dioctyl phthalate particles. The filter should also be unreactive. Good practice requires that a blank be run by sampling filtered flue gas to determine if the filter reacts with the flue gas. The filters are not reused. The filter support media should be glass frit.

Four impingers are connected in series with glass ball joint fittings. The first, third, and fourth impingers are of the Greenberg–Smith design modified by replacing the tip with a 1-cm i.d. glass tube extending to 1 cm from the bottom of the flask. The second impinger is of the Greenberg–Smith design with the standard tip. A condenser may be used in place of the impingers, provided that the moisture content of the stack gas can still be determined. The user may either construct his own sampling train or use one of the commercial models available. Some of the vendors of EPA Method 5 equipment are listed in Table 6.

7.1.2 *Equipment Preparation*

When the equipment reaches the sampling site, it should be carefully uncrated and inspected. The probe should be carefully checked to be sure that it is clean. All glassware should be inspected for damage and damaged glassware replaced. All pumps are leak tested.

An initial velocity traverse should be made to determine the maximum, minimum, and average flow. This information is used to guide the selection of proper nozzle size for isokinetic sampling.

When the proper nozzle size is known, the sampling train can be moved to the stack and sampling can begin.

7.1.3 *Sampling Procedures*

Sampling begins with the probe properly positioned at the first traverse point. The pump is started and the flow is adjusted as needed to give isokinetic conditions. The sampling rate should be adjusted as needed to keep up with process variations. When the time for sampling at the point is over, the probe is moved to the next point and isokinetic conditions are reestablished. A data sheet similar to that shown in Figure 12 should be filled out at 5-min intervals during the sampling.

As soon as sampling is completed, the pump is turned off and the probe is carefully removed from the stack. Once the probe is removed from the stack, the train can be disassembled.

The probe and filter should be moved to a clean area before they are disassembled. While the filter and probe are cooling, the amount of water condensed in the impinger train should be measured and recorded.

When the filter holder is cool enough to be handled, the filter should be removed using tweezers. Care must be taken to ensure that all of the filter is removed and that the collected particulate matter is not disturbed. The filter should be placed in a petri dish and then desiccated before it is weighed.

Plant _____

Location _____

Operator _____

Date _____

Run no. _____

Sample box no. _____

Meter box no. _____

Meter $\Delta H @$ _____

C factor _____

Pitot tube coefficient, Cp _____

Schematic of stack cross section

Barometric pressure _____

Assumed moisture, % _____

Probe extension length, m(ft.) _____

Nozzle identification no. _____

Average calibrated nozzle diameter, cm (in.) _____

Filter no. _____

Leak rate, m^3/min, (cfm) _____

Static pressure, mm Hg (in. Hg) _____

Traverse point number	Sampling time (θ), min.	Vacuum mm Hg (in. Hg)	Stack temperature (T_s), °C (°F)	Velocity head (ΔP_s), mm H_2O (in. H_2O)	Pressure differential across orifice meter, mm H_2O (in. H_2O)	Gas sample volume, m^3 (ft^3)	Gas sample temperature at dry gas meter		Temperature of gas leaving condenser or last impinger, °C (°F)
							Inlet, °C (°F)	Outlet, °C (°F)	
Total							Avg	Avg	
Average							Avg		

Fig. 12 Data form for EPA Method 5 data.

The probe is cleaned using the procedures in the *Federal Register*.[1] The probe catch is dried and then weighed. The amount of particulate matter collected is the sum of the probe catch and the filter catch (the front half of the train). Because the probe catch can be a significant part of the total catch, great care must be taken in cleaning the probe.

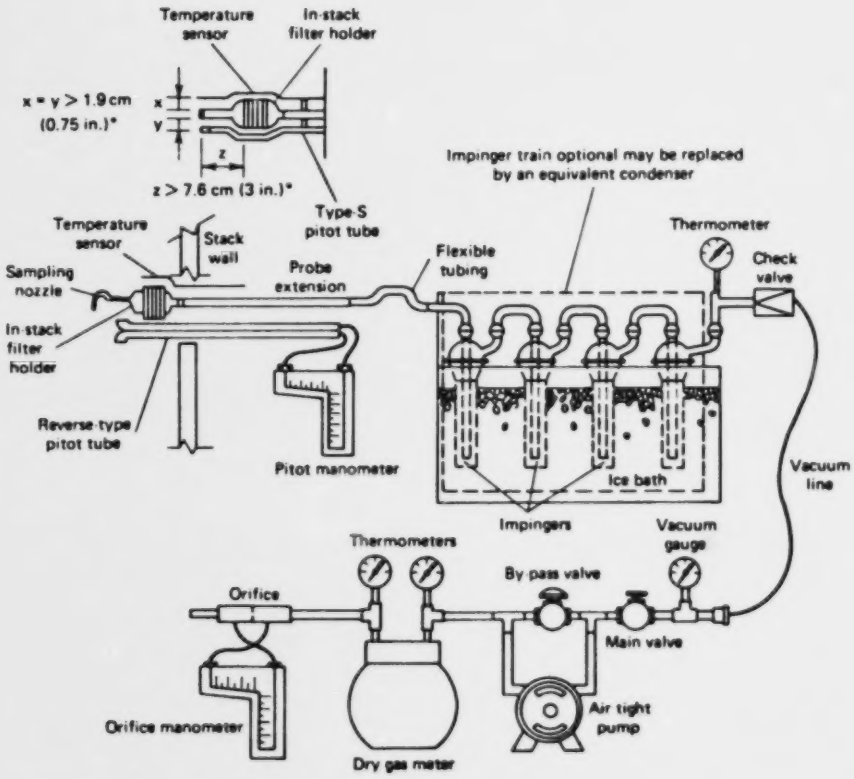
Most EPA regulations require at least three replicates, so the above procedures must be repeated three times to complete the sampling.

7.2 EPA Method 17

The second EPA approved method for mass sampling is EPA Method 17.[6] The primary difference between EPA Method 5 and Method 17 is that an instack filter (shown in Figure 13) is used with Method 17 instead of the heated out-of-stack filter used with Method 5. This means that particulate matter collected by EPA Method 17 is defined as whatever exists as particulate matter under stack conditions. In some cases the measurements made with Method 17 will agree with measurements made with Method 5; and in some cases the two measurements will not agree.

The procedures used with EPA Method 17 are basically the same as those used with EPA Method 5. Isokinetic samples are withdrawn at preselected traverse points. The sampling rate is adjusted to ensure that isokinetic sampling is maintained whenever the traverse point is changed or whenever process conditions change. Data reduction is the same as for Method 5.

The choice of which sampling method should be used depends on the reason for taking the data. In general all sampling should be done using the method required for compliance testing.



*Suggested (interference-free) spacings

Fig. 13 EPA Method 17 particulate sampling train.[6]

7.3 Mass Efficiency Measurement

Both the inlet and outlet mass concentrations are required to determine the mass collection efficiency of a particulate control device. Because of process variations, the inlet and outlet measurements should be made simultaneously. When the device has a very high efficiency, the inlet and outlet mass concentrations can vary by several orders of magnitude. Such large differences in concentration can make simultaneous sampling difficult. But with proper planning, simultaneous inlet and outlet mass sampling is possible.

7.4 Mass Measurement Calculations

The calculations necessary to reduce mass train data are:

1. Calculation of dry sample volume at standard conditions.
2. Calculation of moisture content of the gas.
3. Calculation of the dry molecular weight of the flue gas.
4. Calculation of the average stack velocity.
5. Calculation of the stack volumetric flow rate.
6. Calculation of the particle concentration.
7. Calculation of mass collection efficiency of the device.

The dry sample volume at standard conditions is

$$V_{std} = \frac{V_m T_{std}}{T_m P_m / P_{std}} \tag{5}$$

where V_m is the meter volume, T_{std} is the absolute standard temperature, T_m is the absolute meter temperature, P_{std} is the absolute standard pressure, and P_m is the absolute pressure at the meter. Any set of consistent units can be used.

The moisture content of the gas B_w is

$$B_w = \frac{V_w}{V_{std} + V_w} \tag{6}$$

where V_w, the volume of water collected, is

$$V_w = V_l R T_{std} \frac{\rho_w}{P_{std} + M_w} \tag{7}$$

V_l is the amount of liquid collected, R is the ideal gas constant, ρ_w is the density of water, and M_w is the molecular weight of water.

The molecular weight of the dry gas is given by

$$M_g = 0.44(\%CO_2) + 0.32(\%O_2) + 0.28(\%N_2 + \%CO) \tag{8}$$

The molecular weight of the wet gas is

$$M_s = M_g (1 - B_w) + 18 B_w \tag{9}$$

The average gas velocity in the stack is given by Eq. (2).

The volumetric flow rate through the stack is

$$Q_s = \frac{A_s V_s (1 - B_w) T_{std} P_s}{T_s P_{std}} \tag{10}$$

A_s is the cross-sectional area of the stack. The concentration of particulate matter at standard dry conditions is given by

$$C = \frac{m_p}{V_{std}} \tag{11}$$

where m_p is the mass of particulate matter collected.

If the efficiency of a particulate control device is to be calculated, the concentrations at both the inlet, C_{in}, and the outlet, C_{out}, must be known. The penetration Pt through the device is C_{out}/C_{in}. The efficiency E is $1 - \text{Pt}$.

Basic language computer programs are presented later to do all of these calculations.

8 PARTICLE SIZE DISTRIBUTION MEASUREMENTS

The most important physical property of an aerosol, at least for air pollution, is its particle size distribution. Many of the important properties of the aerosol, such as its collectability and light scattering properties, are determined by the particle size distribution.[7]

Because the particle size distribution is so important, there is a growing need for good measurements of the particle size distribution from air pollution sources.

Particle size distributions are measured by many different techniques. Each technique covers a limited range of particle diameters as is shown in Table 7. Measurements with cascade impactors will be covered in detail in later sections. Only brief descriptions of the other techniques will be given.

8.1 Particle Diameter Conventions

The definition of particle size must be firmly established before further discussion is possible. The terms particle size or 5-μm size particles have no quantitative meaning. For spherical particles, size can mean diameter or radius. For nonspherical particles, the term size can mean almost anything. In most air pollution work, it is generally assumed that the particles are spheres.

There are several different types of particle diameter that are often used in air pollution. The most common diameters are the physical diameter d, the classical aerodynamic diameter d_C, and the impaction aerodynamic diameter d_A. Rabe[8] has presented a lucid discussion of the various diameters, and their use. The defining equations for the various diameters are shown in Table 8.

The impaction aerodynamic diameter is the simplest of the diameters to use, because it does not require solving for the Cunningham correction factor. Calculation of the other diameters requires solving for the Cunningham correction factor.

$$C(d) = 1 + 2A(l/d) \tag{12}$$

$$A = 1.246 + 0.42 \exp[-0.87d/(2l)] \tag{13}$$

where l is the mean free path of air molecules in micrometers which equals $0.0653(760/P)(T/296.2)$, T is the absolute temperature in °K, and P is the absolute pressure in mm Hg. 0.0653 μm is the mean free path of air at 23°C and 760 mm Hg.

The equivalent PSL diameter is also used to describe the diameter measured by light scattering instruments. The equivalent PSL diameter is the particle diameter that has the same light scattering properties of a PSL sphere of the stated diameter. This diameter is used because light scattering instruments are sensitive to the refractive index of light which is generally unknown, because these instruments are calibrated with PSL spheres.

The choice of which diameter should be used depends on the ultimate use of the data. For example, scrubbers are sensitive to the impaction aerodynamic diameter. Thus, d_A should be used in scrubber studies. Electrostatic precipitators are sensitive to the physical diameter of the particle, so d is the appropriate diameter for electrostatic precipitator studies. Whatever diameter is used should be specified.

The equations in Table 8 can be used to convert from one diameter to another.

8.2 Cascade Impactors

The most common instrument used to measure the particle diameter of flue gases is the cascade impactor. The cascade impactor is an inertial instrument which measures the aerodynamic impaction

Table 7 Techniques for Measuring Particle Size Distribution

Technique	Particle Diameter Range
Cascade impactors	$0.3 < d > 15$ μm
Cyclones	$0.3 < d > 15$ μm
Light scattering	$0.5 < d > 10$ μm
Diffusion batteries	$0.01 < d > 0.1$ μm
Mobility analyzer	$0.001 < d > 0.1$ μm

Table 8 Defining Equations for Various Particle Diameters

Name of Diameter	Symbol	Equation
Classical aerodynamic	d_C	$d_C = d\,[\rho C(d)/C(d_C)]^{0.5}$
Impaction aerodynamic	d_A	$d_A = d\,[\rho C(d)]^{0.5}$
Physical diameter	d	$d = d_A/[C(d)]^{0.5}$

$C(d)$ = the Cunningham correction for a particle of diameter d
$C(d_C)$ = the Cunningham correction for a particle of diameter d_C
ρ = particle density

diameter d_A. Most commercial cascade impactors provide data over the range $0.5 < d_A > 12$ μmA. [The usual units for impaction aerodynamic diameter are μmA and μmA = μm(g/cm³)^0.5.]

Some special cascade impactors that operate at low pressure are available to provide data for $d_A < 0.5$ μmA. Although many commercial cascade impactors claim to provide data for $d_A > 12$ μmA, laboratory calibration data[10] show that the upper limit is close to 12 μmA. Probe and nozzle losses also limit the practical upper limit of cascade impactors to about 12 μmA.

8.2.1 *Theory of Cascade Impactors*

A typical cascade impactor has several stages. The larger particles are collected on the upper stages and the finest particles are collected on a backup filter. A typical impactor stage is shown in Figure 14. The particles are accelerated through the jet onto the impaction surface. Because of their inertia, some of the particles will not be able to follow the streamlines and will be collected. The collection efficiency of an ideal cascade impactor stage is shown in Figure 15.

The collection efficiency of a cascade impactor impaction stage is a function of the inertial impaction parameter, K_p.

$$K_p = \frac{d^2 C(d) \rho_p V_j}{9 \mu D_j} \tag{14}$$

where V_j is the gas velocity in the jet, μ is the viscosity of the gas, and D_j is the diameter of the jet. Equation (14) can be rewritten in terms of the impaction aerodynamic diameter as

$$K_p = \frac{d_A V_j}{9 \mu D_j} \tag{15}$$

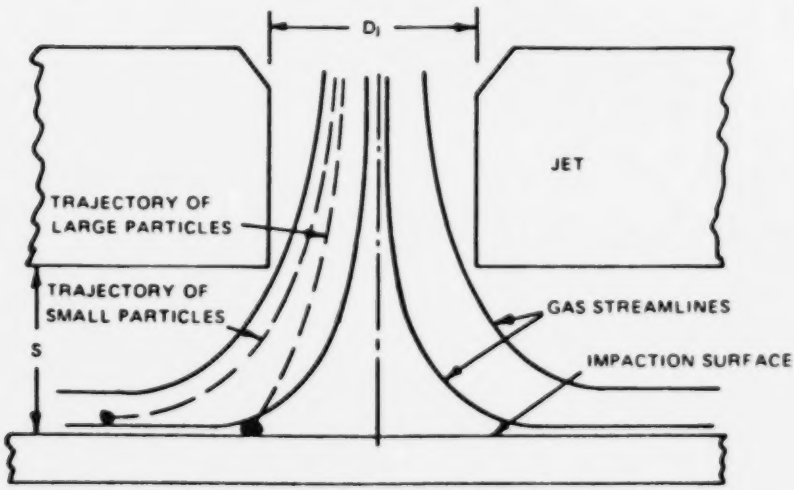


Fig. 14 Typical impactor stage.[3]

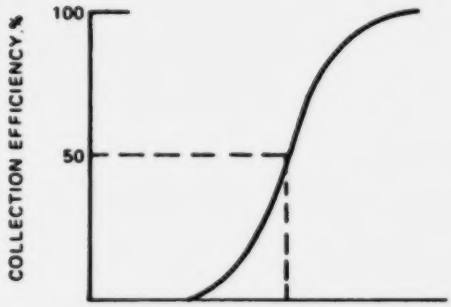


Fig. 15 Ideal impactor efficiency curve.[3]

For the case where the stage efficiency is 50%, that is, the cut point,

$$K_{p50} = \frac{d_{50} V_j}{9\mu D_j} \tag{16}$$

Although there are theoretical equations for K_{p50}, experience has shown that the K_{p50} must be determined by empirical calibration.

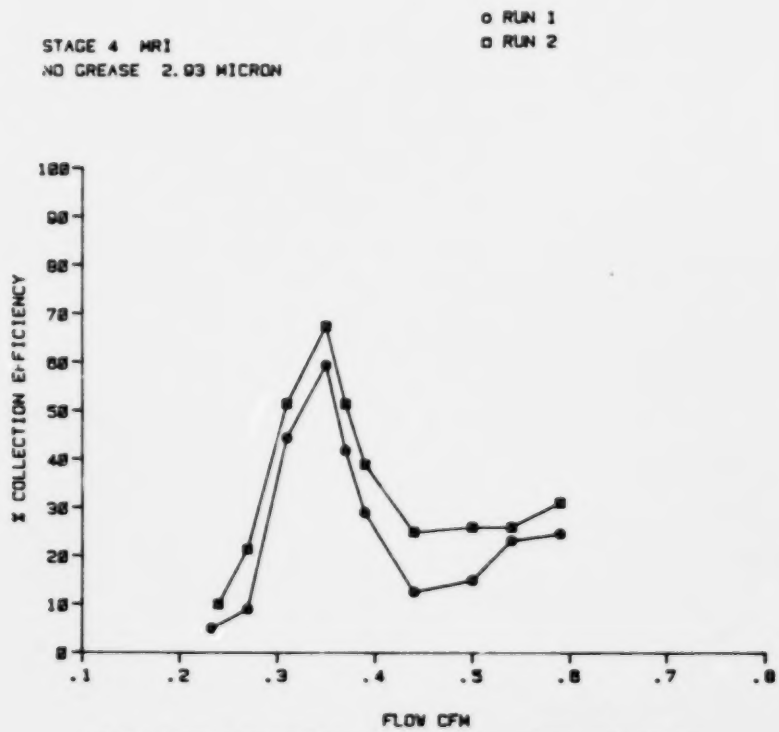


Fig. 16 Impactor stage efficiency with particle bounce bare metal substrate.

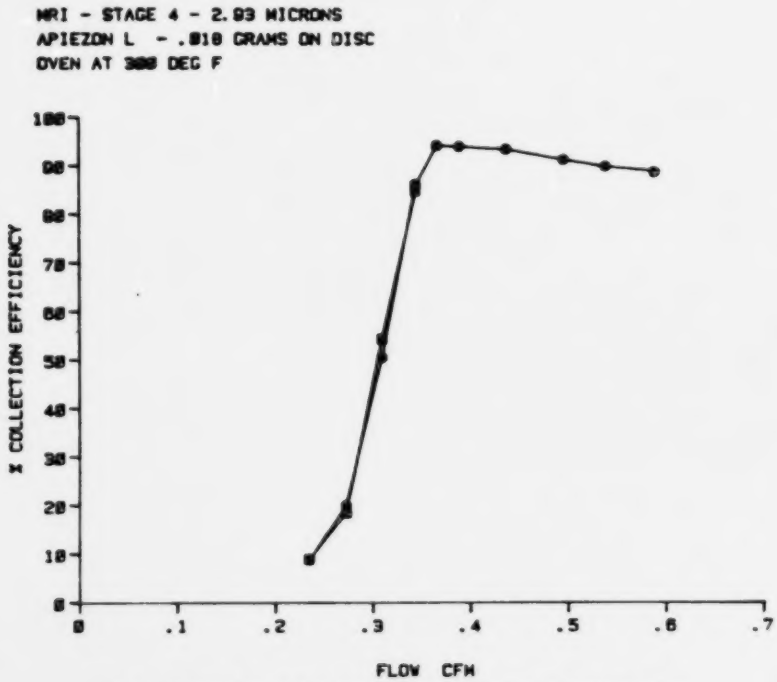


Fig. 17 Impactor stage efficiency with grease substrate to reduce bounce.

8.2.2 *Nonideal Behavior of Cascade Impactors*

The most important nonideal factors affecting cascade impactors are:

1. Particle bounce.
2. Wall losses.
3. Nonideal efficiency curves.

The most serious of the nonideal factors is particle bounce. The basic assumption of cascade impactor use is that particles much larger than the cut point are collected with near 100% efficiency. As can be seen from Figure 16, this can be a poor assumption. The implication of this figure is that if a particle is not collected on the proper stage, it will probably be collected on the final filter. In cases of severe bounce, McCain and McCormack[9] suggest that the final filter should be neglected in the data reduction process.

Particle bounce is made worse if the impactor stage is overloaded with particulate matter. A general rule is that no more than 10 mg should be collected on a stage. Data reported by Esmen and Lee[11] show that if the stage loading is much larger than 10 mg, particle bounce can be a major problem.

The best way to deal with particle bounce is to use a substrate that will prevent bounce. The ability of a suitable substrate to reduce bounce is shown in Figure 17. As will be discussed in Section 8.3.4, substrates can create problems of their own. This means that extreme care must be taken in the selection of substrates.

Cushing et al.[10] have studied the wall losses of many commercial cascade impactors. Some of their results are shown in Figures 18 and 19. These are typical of the wall losses of well-designed cascade impactors. Note that the wall losses are quite low for particles with diameters less than 10 μm. The conclusion of these data is that wall losses are not a problem in well-designed cascade impactors unless data on large particles are desired.

The fact that cascade impactors have nonideal efficiency curves is best dealt with by careful laboratory calibration of cascade impactors before their use. Failure to calibrate the cascade impactors can result in significant and avoidable errors.

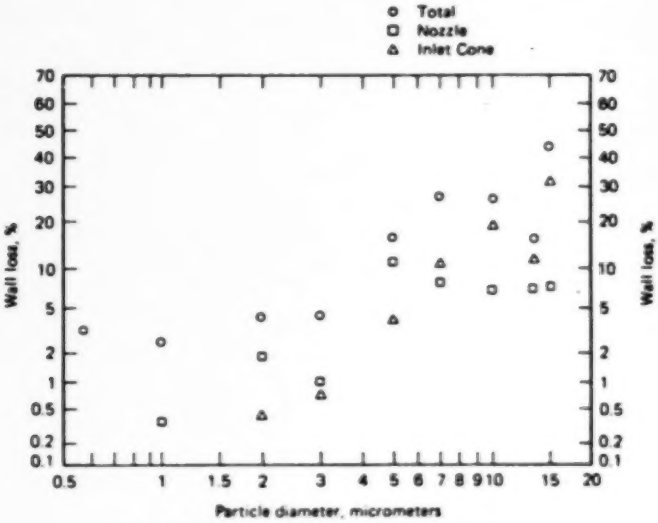


Fig. 18 Wall losses for Andersen stack sampler.[10]

8.2.3 *Cascade Impactor Calibration*

Cascade impactors, the same as other instruments, should be calibrated before they are used and periodically recalibrated with use. Impactors should also be recalibrated whenever visual inspection of the cascade impactor shows that the hole size or shape has changed. Failure to calibrate the impactor can introduce significant errors into size distribution measurements.

The calibration procedure reviewed here is from *Cascade Impactor Calibration Guidelines* by S. Calvert, C. Lake, and R. Parker, EPA Report EPA-600/2-76-118, also available as Appendix B to *Procedures for Cascade Impactor Calibration and Operations in Process Streams*, EPA Report EPA-600/2-77-004. This procedure is designed to calibrate the lower stages of a cascade impactor. Calibration of the upper stages is significantly more time consuming and will be reviewed later in this discussion.

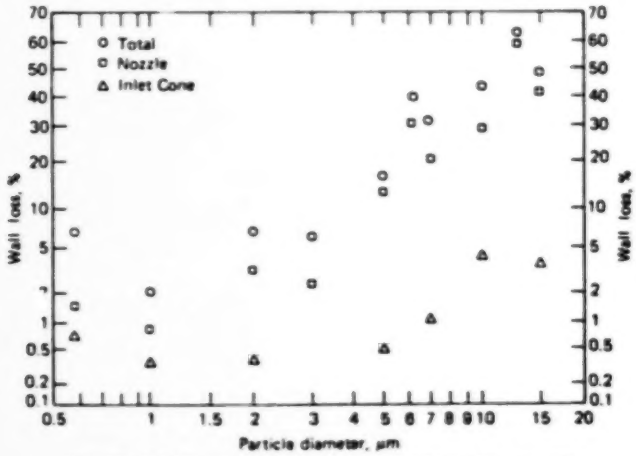


Fig. 19 Wall losses for University of Washington impactor.[10]

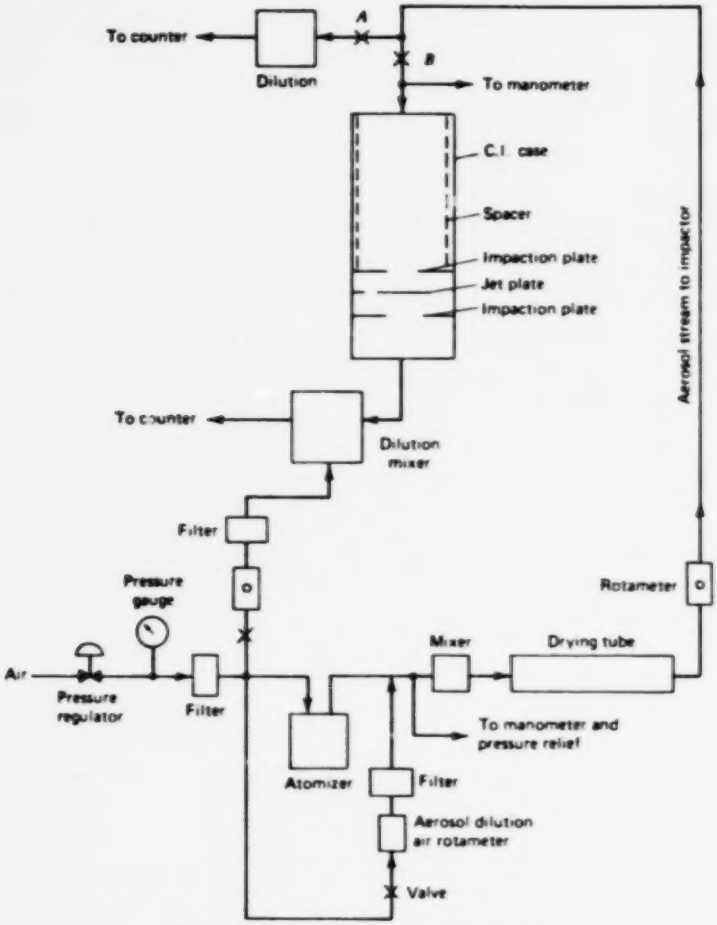


Fig. 20 Cascade impactor calibration setup.[13]

The primary objective of the calibration procedure is to determine the cut point of each impactor stage. The particle size distribution of an aerosol can be calculated from impactor data if the cut points of the stages are known and if particle bounce is minimized.

Because the calibration is intended to determine the cut point of the impactor, calibration efforts for each stage should be concentrated on obtaining data using gas flow rates and particle diameters typical of normal impactor operation. In general, particle diameters from 0.3 to 3 μm are adequate to cover the lower several stages of most commercial cascade impactors.

The experimental equipment for the calibration is shown in Figure 20. The major pieces of equipment are:

1. Aerosol generator for monodisperse particles.
2. Drying tube to remove residual water from particles.
3. Flow measuring equipment.
4. The cascade impactor stage being calibrated.
5. A particle counter to measure the particle concentration entering and leaving the cascade impactor stage.

Table 9 PSL Particles for Impactor Calibrations

Average Diameter, μm	Standard Deviation, μm	Density, g/cm³
0.087	0.0046	1.05
0.091	0.0058	1.05
0.109	0.0027	1.05
0.176	0.0023	1.05
0.234	0.0026	1.05
0.255	0.0022	1.05
0.312	0.0022	1.05
0.357	0.0056	1.05
0.364	0.0024	1.05
0.481	0.0018	1.05
0.600	0.0030	1.05
0.721	0.0057	1.05
0.801	0.0035	1.05
0.822	0.0043	1.05
1.011	0.0054	1.05
1.101	0.0055	1.05
2.02	0.0135	1.0275
5.7	1.5	1.027

The particles used to generate the aerosol are polystyrene latex (PSL) spheres available from Dow Chemical Corporation. The available particle diameters are shown in Table 9. Note that although large diameter PSL spheres are available, they are generally not suitable for cascade impactor calibration. Problems in generating the aerosol and transporting the aerosol to the cascade impactor stage being calibrated generally make it difficult to use PSL spheres much larger than 3 μm in diameter.

The first step in the calibration is to make up a dilute solution of the PSL by diluting the stock solution. The diluted solution is used to generate an aerosol which is collected and then examined under a microscope. If doubles run more than 2 to 5%, additional dilution is required. This step must be followed for each diameter of PSL used in the calibration.

Once the required PSL dilutions are determined, the calibration can proceed. Each stage should be calibrated over the range of about $0.1 < K_p < 0.3$ to ensure adequate data. The K_p can be varied by varying the flow rate over a small range and by using more than one particle diameter. Both means of varying K_p should be used.

The penetration of particles through the impactor stage is measured using a particle counter. The particle counter is first used to measure the number of particles entering the impactor stage and then used to measure the number of particles leaving the stage. The measurement is repeated and then the flow rate or the particle diameter is changed to give a new K_p and the process repeated. When the desired range of K_p for a given stage has been studied, the process is repeated for the next stage and so on until all the stages of the impactor are calibrated.

The penetration for each K_p is determined from $Pt = C_{out}/C_{in}$ where Pt is the penetration, C_{out} is the particle concentration leaving the impactor stage, and C_{in} is the particle concentration entering the stage. A plot of Pt versus K_p is made for each stage. The K_{p50} is determined from the plot.

The calibration of the large particle stages of a cascade impactor is not possible using the above procedure. Cushing et al.[10] have conducted calibrations of the large particle diameter stages of many commercially available impactors. Their procedure consists of generating a monodisperse aerosol of known particle diameter and concentration. The aerosol is then sampled with an impactor. The concentration of particles collected is determined and plots of penetration versus K_p are made.

Typical calibration data for an impactor are shown in Table 10.

8.2.4 *Cascade Impactor Substrates and Substrate Problems*

As mentioned in Section 8.2.2, cascade impactors must be used with a suitable substrate to reduce the adverse effects of particle bounce. Failure to use a proper substrate can result in totally wrong data which is worse than no data at all.

The common substrates are either greases or filter mats. Each type of substrate has its advantages and disadvantages. Also the type of substrate used affects the collection efficiency curve of the cascade impactor stage.

The effect of substrate on collection efficiency is shown in Figure 21 which compares a grease substrate with a fiberglass filter. Note that the grease gives more ideal behavior than does the filter.

Table 10 Values of Stage Constants for MRI and University of Washington Impactors

Stage	MRI* C_i	University of Washington C_i
1	5.4069×10^{-3}	7.4123×10^{-3}
2	6.8611×10^{-3}	9.3954×10^{-3}
3	2.1484×10^{-3}	1.3376×10^{-3}
4	3.8666×10^{-3}	1.7759×10^{-3}
5	1.0147×10^{-3}	1.8378×10^{-3}
6	3.5065×10^{-4}	4.2206×10^{-4}
7	2.2899×10^{-4}	1.0104×10^{-4}

* MRI stage constants for stages 4, 5, 6, and 7 are based on EPA/IERL-RTP/Particulate Technology Branch impactor calibration data. University of Washington stage constants and MRI stage constants for stages 1, 2, and 3 are based on Southern Research Institute calibration data.

The fact that the substrate affects the collection efficiency of the impactor means that the impactor must be calibrated using the same substrate or substrates as will be used in the field test. Otherwise, the calibrations are not useful.

The major problems with substrates are weight losses due to handling, weight gains or losses due to reaction with flue gas, and deterioration of the substrate so that it no longer functions.

Weight losses can be a problem with filter substrates if they are not handled properly. Periodic checks of handling procedures should be made by assembling and then disassembling an impactor. If the substrates show any weight change, the handling procedure needs to be reviewed.

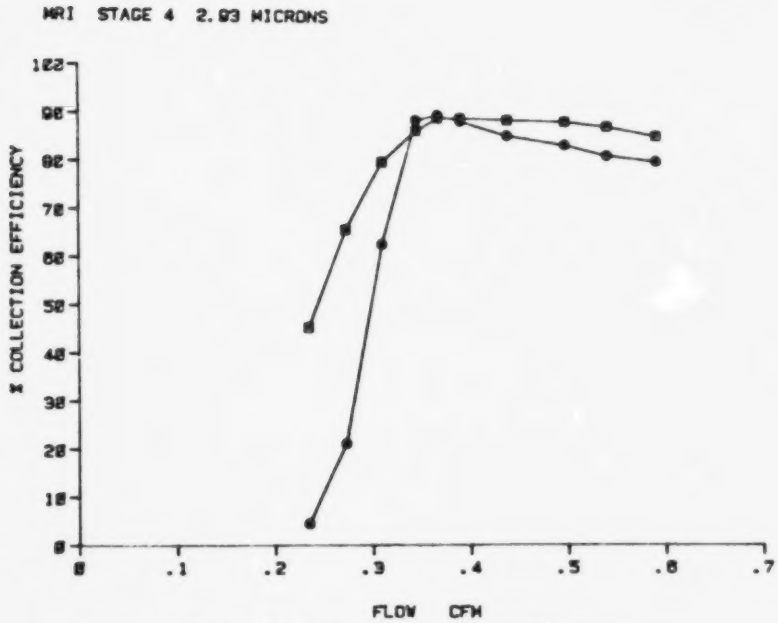


Fig. 21 Effect of substrate on impactor efficiency curve.

Grease substrates are not subject to weight losses due to handling. However, too much grease can result in weight loss due to blowoff. That is, the excess grease is blown off the impactor collection stage. Blowoff is checked for by running blanks.

Substrate weight changes due to reactions with the flue gas can be a major problem with field use of cascade impactors. Both grease and filter substrates are affected by this problem. An example of the severity of the problem of weight gain is shown in Table 11.[13] Note that the weight gain is a significant fraction of normal stage loading which can be less than 1 mg on the lower stages.

Deterioration can be caused by high temperature and/or reactions with the flue gas. If any doubts exist as to the effectiveness of a substrate, use another one. The best test for deterioration is to subject a blank to the flue gas environment and then use the blank as the substrate in a calibration run. If the substrate has deteriorated, the calibration curves would show severe particle bounce.

The only way to find the proper substrate for a given field test is to run blanks. The first step in running a blank is to assemble the cascade impactor just as if a normal run were to be made. Then a filter holder with a double filter is placed in front of the cascade impactor nozzle. Finally, the cascade impactor with filter in front is inserted into the flue gas and normal sampling procedures followed. At the end of the run, the blank cascade impactor is handled the same as a normal impactor. It is disassembled, substrates allowed to dry, and then the substrates are weighed. Any weight changes observed in the blank are due to gas substrate reactions or improper handling.

Because the normal weight change for a cascade impactor stage is at best a few milligrams, especially for the lower stages, any blank weight change is a serious matter. At times the blank weight change can exceed the weight gain expected from particles.

If a suitable substrate cannot be found, then substrate conditioning should be tried. Unfortunately, conditioning is a slow process.

The following procedures for conditioning fiberglass filter substrates are taken from Harris.[14]

Extensive laboratory and filed experiments have been performed to find a suitable filter to be used as impactor substrates. To date the only suitable material is Reeve Angel 934AH available from Whatman, Inc., 9 Bridewell Place, Clifton, NJ 07014. When this material is treated according to the procedure outlined below, mass gains due to reactions with flue gas can be kept to a minimum. Glass fiber backup filters should exhibit the same behavior and should be treated in the same manner.

Procedure for Acid Washing Substrates

1. Submerge the glass fiber substrate in a 50–50 mixture (by volume) of distilled water and reagent grade concentrated sulfuric acid at 100–115°C for 2 hr.
2. When the substrates are removed from the acid bath, they should be allowed to cool to room temperature. Next they are rinsed in flowing distilled water (flow rate 10–20 cm^3/min). The pH of the rinse water should be monitored. Rinsing can stop when the pH of the rinse water is the same as the pH of the distilled water. The importance of complete washing cannot be overemphasized.
3. Next the substrates are rinsed in reagent grade isopropanol for several minutes. This step should be repeated five times with fresh isopropanol.
4. Dry the substrates at room temperature and then bake them at 50°C for 2 hr, at 200°C for 2 hr, and finally at 370°C for 3 hr.

Shred two of the substrates and place the pieces in distilled water for about 10 min and then measure the pH. If the pH is lower than that of distilled water, bake the filters at 370°C for 4 hr to drive off residual sulfuric acid.

Even after acid washing, excessive weight gains have been found in some situations. In such cases,

Table 11 Substrate Weight Gain Due to Reaction[13]

Stage	Weight, mg
0	1.21
1	0.54
2	0.46
3	0.52
4	0.37
5	0.46
6	0.37
7	0.47
8	0.45
Filter	1.03

the acid washed substrates should be subjected to in situ conditioning. In situ conditioning is accomplished by exposing the filters to filtered flue gas for 6 to 24 hr.

After the substrates have been completely conditioned, they should be desiccated and then weighed for use.

Field sampling should not proceed until a suitable substrate is found.

Sometimes, no suitable substrate can be found. In such a case, the blank weight gain (or loss) can be subtracted from the particulate weight gains, provided that the standard deviation of the substrate weight changes is small.

Blank runs to determine a suitable substrate should be run as part of the presite survey. Also at least one blank run should be conducted during each day of testing. The results of the blank run should be reported as part of the impactor data report.

Note that the final filter and mass filters are also subject to weight changes due to flue gas reactions and should be included in the blank runs.

8.2.5 *Impactor Procedures*

The procedures for using cascade impactors are not as well specified as are the procedures for mass sampling. The procedures presented here are based on the experience of many individuals, especially Dr. S. Calvert, B. E. Daniel, Dr. D. S. Ensor, D. B. Harris, G. Ramsey, and Dr. W. B. Smith. Additional details on the procedures for using cascade impactors can be found in several EPA publications[15,16,17] listed in the references.

A typical cascade impactor train is shown in Figure 22.

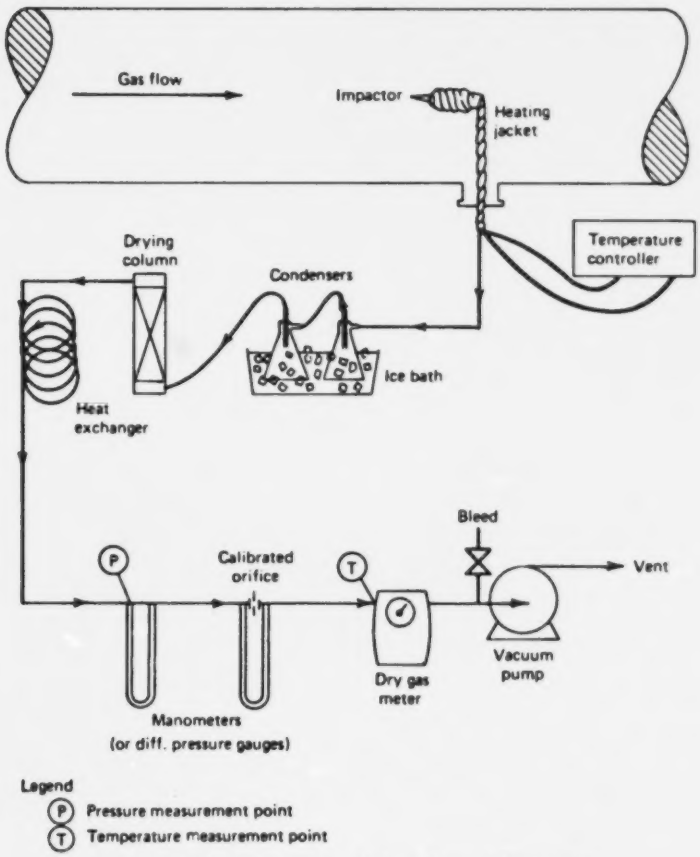


Fig. 22 Typical sample train with heated instack impactor.[14]

8.2.5.1 Presite Survey. The first step in conducting a cascade impactor test program is to gather as much information as is required to adequately prepare for the test. Minimum data are the identification of special or unusual problems, identification of potential substrates, and the initiation of work on tasks which must be completed prior to the testing (e.g., installation of ports). A form for the presite survey is given by Harris[14] and is reproduced as Table 12.

An impactor run and a blank run should be conducted as part of the presite survey. This impactor run will provide information on likely loading and will be useful in selecting sampling equipment. The blank run will enable selection of substrates.

A site for the impactor setup and disassembly should be located during the presite survey. Also a suitable location for weighing must be located. The weighing site must be free from vibration, which means that many locations in the plant are not suitable. If a suitable location in the plant is not available, the weighing can be conducted in a motel room.

Based on the information collected during the presite survey, the decisions shown in Table 13 can be made.

8.2.5.2 Field Test Procedures. As soon as the equipment is on site, it should be carefully unpacked and inspected for damage. The balance should be set up and field calibrated. A blank run should be made to ensure that the substrate selected is adequate.

A velocity traverse should be conducted to map the flow and locate suitable points to run the impactors. Note that because the flow rate of the impactor cannot be adjusted without affecting the cut points, it is impossible to traverse the duct and maintain the isokinetic sampling rate. In practice this means that impactor sampling is done at a very few points in the duct. Two points is a minimum.

Table 12 Preliminary Survey for Particulate Sizing

Plant Data Date: _____

Company name: _____

Address: _____ City: _____ State: _____

Name of contacts: _____ Title: _____

_____ Title: _____

_____ Title: _____

Telephone number: _____

Process description: _____

(Operating schedule): _____

(Batch or continuous): _____

(Rate/variability): _____

Air Pollution Control Equipment

Description: _____

(Operating schedule): _____

(Rate/variability): _____

Sketch of Sampling Sites (with approximate dimensions, ports located, upstream and downstream equipment if important).

Table 12 *(Continued)*

Conditions at Sampling Sites

Pressure _____

Temperature _____

Gas rate _____

Gas composition _____

Particulate loading _____

Precutter required? _____

Approx. size dist. _____

Weight gain/loss
by substrates, filter _____

Weight gain/loss
by grease _____

Particulate condition—
hard, sticky, etc. _____

Wet or dry _____

Port size/fitting type _____

Condensation? _____

Notes _____

1. Electricity source
   a. Amperage per circuit _____
   b. Location of fuse box _____
   c. Extension cord lengths _____ Quantity _____
   d. Adapters needed _____
   e. Electrician _____
2. Safety equipment needed
   a. Hard hats _____ d. Safety shoes _____
   b. Safety glasses _____ e. Alarms _____
   c. Goggles _____ f. Other _____
3. Ice
   a. Vendor _____
   b. Location _____
4. Solvents
   a. Vendor _____
   b. Location _____
5. Sampling ports
   a. Who will provide? _____ Welder: _____
   b. Size opening _____
6. Scaffolding
   a. Height _____
   b. Length _____
   c. Vendor _____
      Address _____
      Telephone _____

Table 12 (*Continued*)

7. Distilled water
   a. Vendor _____
   b. Location _____
8. Test site facilities
   a. Parking _____
   b. Restroom _____
   c. Laboratory facilities _____
   d. Cleanup area _____
9. Motels:
   a. _____ Phone _____ Rate _____
   b. _____ Phone _____ Rate _____
   c. _____ Phone _____ Rate _____
10. Restaurants:
   a. Near plant _____
   b. Near motel _____
11. Airport convenient to plant _____ Distance _____
12. Comments: _____

Survey by: _____

A mass sample should be obtained to help determine the sampling times. Once the velocity traverse and mass sample are completed, the decisions about impactor type, nozzle size, flow rate, and sampling time can be made. Figure 7 can be used to determine the nozzle size and sampling flow rate for isokinetic sampling. Figure 23 can be used to estimate the sampling time. Experience has shown that a 50-mg sample will generally provide weighable quantities of particulate matter on all stages while preventing stage overload on any stage.

Once the decisions concerning impactor type, nozzle size, flow rate, and sample time are made, the impactor train can be assembled. Assemble the train carefully making sure that the substrates (which should have been preweighed) are not damaged during assembly. Handle the substrates with tweezers. Make sure that the impactor is assembled properly and that the O rings and substrates are not cut when the impactor is put together.

The general guidelines shown in Table 14 should be followed. More specific procedures are given in Table 15.

8.2.5.3 Sample Handling and Weighing. After the impactor run has been completed, the impactor should be transported to the disassembly area. The impactor must be disassembled with care to avoid cutting the substrates and disturbing the particulate deposit.

The impactor should be disassembled one stage at a time. Place the substrate for the stage being disassembled in a petri dish or other container (the same container that it was originally weighed in). Carefully brush any particulate on the bottom of the jet stage into the container. Repeat the procedure for each of the stages.

Desiccate the substrates and then weigh them, recording the results on the data sheet. The balance used for weighing should have a sensitivity of at least 0.05 mg. The weighing procedure should be worked out beforehand and in consultation with the manufacturer of the balance. Proper weighing is of utmost importance.

Table 13 Impactor Decision Making

Item	Basis of Decision	Criteria
Impactor	Loading and size estimate	a. If concentration of particles smaller than 5.0 μm is less than 0.46 g/am³ (0.2 gr/acf), use high flow rate impactor (≈0.5 acfm). b. If concentration of particles smaller than 5.0 μm is greater than 0.46 g/am³ (0.2 gr/acf), use low flow rate impactor (≈0.05 acfm).
Sampling rate	Loading and gas velocity	a. Fixed, near isokinetic. b. Limit so last jet velocity does not exceed: 60 m/sec greased 35 m/sec without grease.
Nozzle	Gas velocity	a. Near isokinetic, ±10%. b. Sharp edged; minimum 1.4 mm ID.
Precutter	Size and loading	If precutter loading is comparable to first stage loading, use precutter.
Sampling time	Loading and flow rate	a. Refer to Section 5.5. b. No stage loading greater than 10 mg.
Collection substrates	Temperature and gas composition	a. Use metallic foil or fiber substrates whenever possible. b. Use adhesive coatings whenever possible.
Number of sample points	Velocity distribution and duct configuration	a. At least two points per station. b. At least two samples per point.
Orientation of impactor	Duct size, port configuration, and size	Vertical impactor axis wherever possible.
Heating	Temperature and presence of condensible vapor	a. If flue is above 177°C, sample at process temperature. b. If flue is below 177°C, sample at 11°C above process temperature at impactor exit external heaters.
Probe	Port not accessible using normal techniques	a. Only if absolutely necessary. b. Precutter on end in duct. c. Minimum length and bends possible.

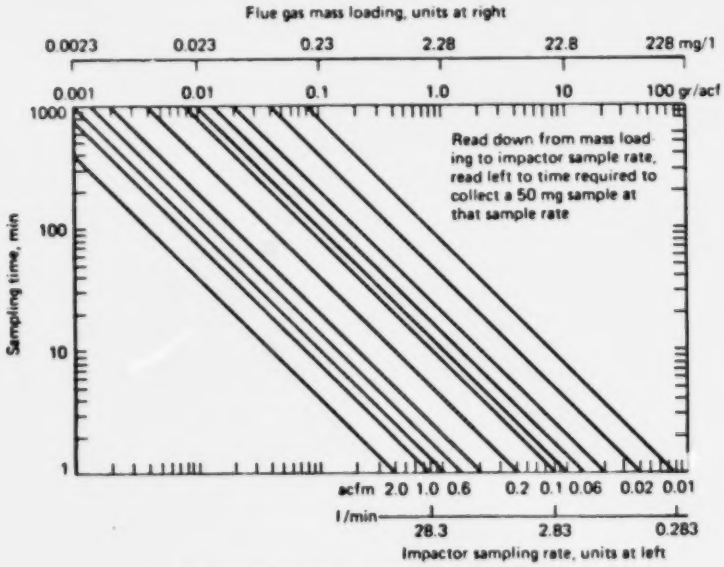


Fig. 23 Time required to get 50-mg sample.[14]

Table 14 Impactor Guidelines

The following procedures should be followed to ensure that cascade impactor data are useful.

1. All impactors should be calibrated following the guidelines in Calvert et al.[13]
2. Bare metal substrates should not be used except in special situations where the particles are sticky.
3. Blank impactors should be run to determine the suitability of a substrate.
4. Grease substrates are preferable to filter substrates.
5. Runs with a weight gain of over 10 mg on any stage should be regarded as suspect.
6. All impactors should be visually inspected before use and any suspect impactors recalibrated.
7. All impactors should be leak tested at temperatures similar to those encountered in field testing.
8. A complete data log should be maintained so that the conditions of each individual run can be reconstructed later.

8.2.6 *Impactor Data Reduction*

Data reduction for cascade impactors consists of three steps if particle size distributions are desired and six steps if particle collection efficiency as a function of particle diameter is calculated. The steps are:

1. Calculation of dry sample volume at standard pressure and temperature.
2. Calculation of the gas flow rate through the impactor at stack conditions.
3. Calculation of impactor cut points.
4. Calculation of cumulative size distribution.
5. Calculation of differential size distribution.
6. Calculation of collection efficiency as a function of diameter.

The equations for the first two steps are presented in Section 5.2 and will not be repeated here. The mathematics for calculation of the impactor cut point, that is, the diameter that is collected with 50% efficiency, are straightforward.

$$d_{50A} = \frac{C_i}{Q_i \times 10^{-3}\,\mu}\ \mu\text{mA} \tag{17}$$

Table 15 Procedures for Field Use of Impactors[13]

1. Obtain a velocity traverse and stack pressure reading using EPA2.
2. At the selected test point in the duct, compute the isokinetic sampling velocity.
   a. The inlet with a high dust concentration will normally require a small nozzle and low sampling rates. Also short sampling times will be required.
   b. The outlet of a particulate control device will normally have lost dust concentrations and will require a larger nozzle and higher sampling flow rates. Also long sampling times will be required to ensure that weighable quantities of particulate are collected on the stages.
3. The impactor train should be carefully assembled. All fittings and joints should be wrapped with Teflon tape. The whole impactor train must be leak tested before and after the test. This is accomplished by plugging the inlet and turning on the sampling pump. An acceptable leak rate is less than about 2% of the sampling rate at a vacuum of greater than 250 mm Hg.
5. The impactor should be preheated for at least 45 min in the stack. During the preheat the nozzle should be pointed downstream.
6. Fill in the data sheet.
7. Start the run by turning the impactor into the flow, opening the probe valve, and setting the desired flow rate.
8. During the run record the test train parameters in systematic time intervals. (For example, in a 1-hr run recording should be made every 10 min. In a 10-min run recordings should be made every minute.)
9. End the test by shutting off the pump and probe valve. Carefully remove the impactor from the port. Perform the post-test leak test.
10. Remove the hose and drain the impinger.
11. After the probe has cooled somewhat, remove the impactor and transport it to the disassembly area.

where C_i is the empirical stage constant, Q_i is the flow rate for the ith stage in L/min, μ is the gas viscosity in poise, and d_{50A} is the aerodynamic cut point in μmA. C_i for some commercially available impactors are given in Table 16. These values of C_i are based on laboratory calibration of the various impactors. The references for the calibrations are also shown in the table. If empirical calibration data for the specific impactors being used are not available, the stage constants in this table should be used. The use of empirical stage constants for the specific impactors being used is strongly suggested and the use of the data in Table 16 is only a stopgap until the impactors are calibrated.

The impaction aerodynamic diameter can be converted to the physical diameter by trial-and-error solution of the following equations:

$$d = \frac{d_a}{[\rho C(d)]^{0.5}}\ \mu\text{m} \tag{18}$$

$$C(d) = l + 2A\frac{l}{d} \tag{19}$$

$$A = 1.246 + 0.42\exp\left(\frac{0.87d}{2l}\right) \tag{20}$$

$$l = 0.653\left(\frac{760}{P\ \text{mm Hg}}\right)\left(\frac{T°\text{K}}{296.2}\right) \tag{21}$$

where l is the mean free path of the gas and ρ is the particle density in g/cm³.

Because there is a finite pressure drop across an impactor, the flow rate across each stage must be corrected for this pressure drop. The pressure drop for each stage must be estimated because the pressure drop across the whole impactor is what is measured. Because the gas flow through the impactor is accelerated and decelerated at each stage, it is reasonable to assume that the pressure drop is due to loss of velocity pressure. Therefore, the pressure drop at each stage is related to the square of the jet velocity. So for the ith stage,

$$DP_i = kV_i * V_i \tag{22}$$

where k is a constant. For many of the commercial impactors, the total pressure drop is low and can be neglected for a first cut at data reduction.

The next step in the data reduction process, after the cut points are calculated, is to construct a cumulative less than stated diameter size distribution. This is done by taking the individual stage weights, and is calculated as follows:

$$M_i = \sum_{i=0}^{N} M_i \tag{23}$$

$$f_i = \sum_{j=0}^{j=i-1} M_j M_i^{-1} \tag{24}$$

Note that because this is a cumulative less than size distribution $j = 0$ corresponds to the backup filter, $j = 1$ corresponds to the stage with the smallest cut point, and $j = N$ corresponds to the stage with the largest cut point.

Table 16 Impactor Stage Constants*

Stage	MRI C_i	Univ of Wash C_i	Brink Grease C_i	Brink Glass C_i
1	0.054069	0.074123	0.004053	0.003562
2	0.068611	0.093954	0.0008918	0.001262
3	0.021484	0.013376	0.0040528	0.0003711
4	0.0038666	0.0017759	0.0002577	[illegible]18747
5	0.0010147	0.0018378	0.000046122	0.[illegible]09852
6	0.00035065	0.0004221	0.000035934	0.00005547
7	0.00022899	0.00010104	0.000011452	0.000011452

* All data for stages 1, 2, and 3 based on work done by Southern Research Institute. Data for MRI stages 4, 5, and 6 from Particulate Technology Branch IERL-RTP. All other data from work done by Southern Research Institute.

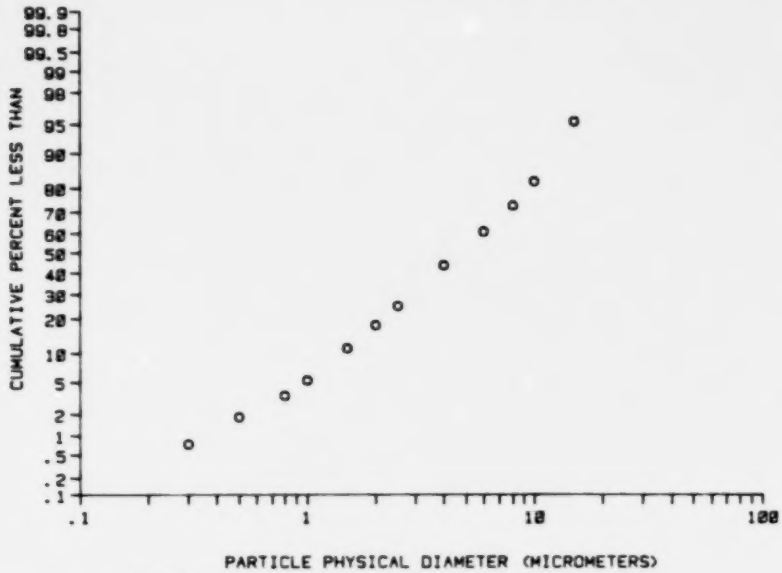


Fig. 24 Typical impactor data plotted on log probability paper.

When the f_i are calculated they can be plotted for display. Experience has shown that in most cases the data tend to give a straight line if they are plotted on log probability paper. See Figure 24.

The next step in the data analysis process is to calculate the differential size distribution curve. This curve provides information on the amount of material in each particle diameter increment. Differentiation of data is a very difficult problem. It is not something that should be done lightly. At present the best way to differentiate the cumulative curve is by use of a spline fit to the data.[19,20]

The final step in the data reduction process is the calculation of the collection efficiency as a function of particle diameter. This is a straightforward calculation performed by dividing the outlet differential size distribution by the inlet size distribution.

A major problem that occurs when the efficiency is calculated is that the inlet and outlet impactors do not give exactly the same cut points, especially at the upper and lower bounds of the size distribution. This means that either the data have to be extrapolated or that efficiency calculations be limited to the overlap region. Sparks[20] has shown that even if the efficiency calculation is limited to the overlap region, serious errors may be introduced into the efficiency calculation if the inlet and outlet impactor cut points are not well matched. The problem of errors due to imperfect match of the inlet and outlet impactors can be overcome if the data are transformed to log normal space and if a spline fit is used to perform the differential calculations and the interpolation between data points.

It is impossible to do all of these calculations by hand in a reasonable time. Fortunately, the recent development of powerful programmable calculators and small microcomputers makes it possible to mechanize all the data reduction. Programs for the Texas Instruments TI-59 Calculator,[20] large computers,[21] and for the Radio Shack TRS-80 microcomputer[22] have been published. Computer programs for the TRS-80 microcomputer are presented at the end of this chapter.

8.2.7 *Data Presentation*

After all the calculations have been completed and checked, it is time to write the report and present the data. There are numerous ways to present the data, but those suggested here have been found useful and informative.

The first thing to remember is to define what particle diameter is being used. Each table and figure should be labeled to show what particle diameter is being used.

The first set of data to present is the cumulative size distribution curves. The most useful way to present them is as plots of cumulative fraction or percent less than the stated diameter plotted on log probability paper. The total mass concentration should be indicated in the title of the curve.

The next set of data to present is the $dM/d \log d$ curves. These curves should be plotted as $dM/d \log d$ versus particle diameter on log–log paper. If there is a large amount of data, it is best

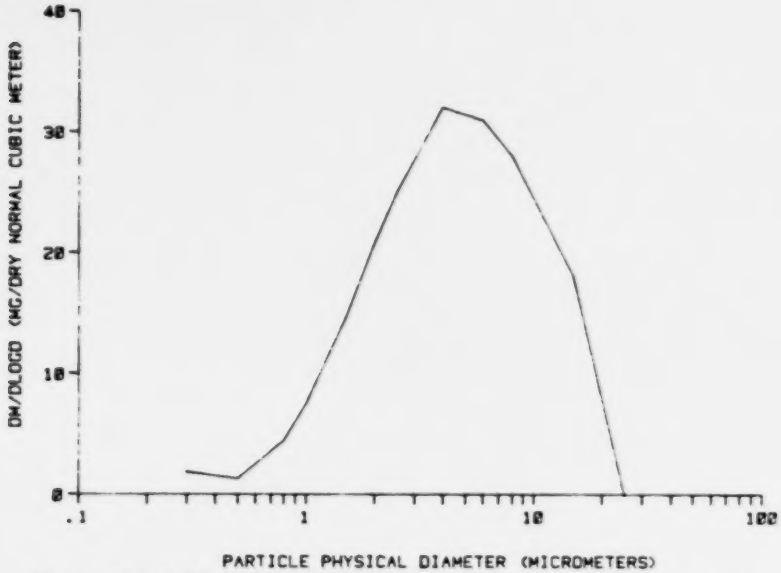


Fig. 25 Typical differential size distribution $dM/d \log d$ vs $\log d$ for physical diameter.

to present average inlet and outlet cumulative and $dM/d \log d$ curves in the body of the report. The curves for each run can be presented in an appendix.

Finally, the penetration as a function of diameter should be presented. These data should be presented as curves of penetration versus diameter. The curves should be plotted on log–log paper.

Examples of all these curves are shown in Figures 24 to 26.

All of the raw data, including stage weights, flow rates, gas temperatures, and so on, should be

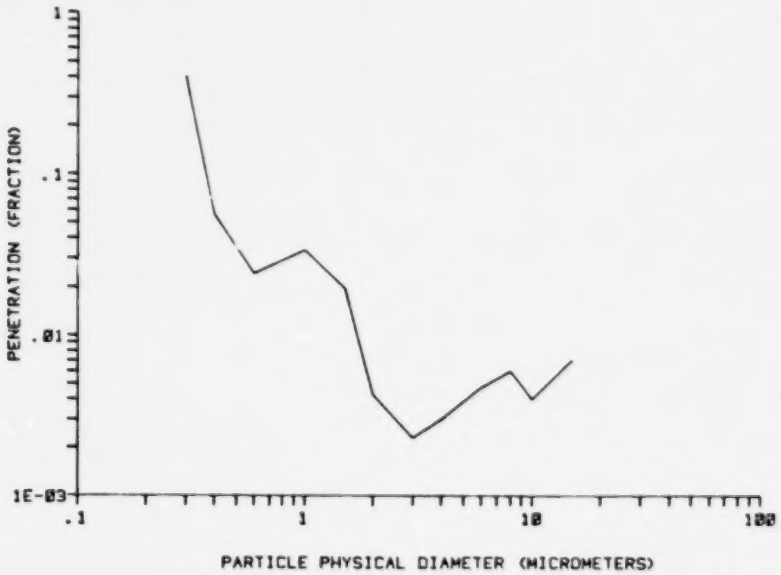


Fig. 26 Typical penetration versus physical diameter curve for impactor data.

presented in an appendix to the report. These data are necessary if someone wants to recalculate the data if, for example, it is found that the impactor calibrations are wrong.

Unless there is an obvious problem with a data set, all of the data should be presented in the appendix. If a data set has too high stage weights, or if a problem with the data set is noted in the field notebook, it should be rejected and not included in the data analysis or the appendix.

Careful attention to how the data are presented can make the data more useful. Of course if the data are to be presented in a paper for publication, it is impossible to include all of the data in the paper. But somewhere there should be a permanent record of all the data.

8.2.8 *Manufacturers of Impactors*

Some manufacturers of cascade impactors are listed in Table 17.

8.3 Other Ways to Measure Particle Size Distribution

Although the cascade impactor is the most common instrument used to measure particle size distribution in flue gases, there are other instruments that are sometimes used. Cyclone sampling trains have been used to collect large amounts of particulate matter in the same diameter range as cascade impactors. Diffusion batteries and mobility analyzers have been used by several groups to obtain data on particles with diameters smaller than 0.5 μm.

All of the instruments mentioned above are special-purpose instruments and will not be discussed in detail here.

8.3.1 *Cyclone Sampling Trains*

Small diameter cyclones have been used to collect large amounts of particulate matter in the same range of particle diameters as covered by cascade impactors. The main advantage of cyclones is that large quantities of material may be collected for chemical or other analysis. The main disadvantage of cyclones is the uncertainty of the cut points. Smith and Wilson[33] have reported on the development of cyclone sampling trains and should be consulted for additional information.

8.3.2 *Diffusion Batteries*

A diffusion battery sizes particles based on their diffusion coefficients. Diffusion batteries may be of parallel plate design, parallel tube design, or of screen design. Particles with high diffusivity are collected in a short time and particles with lower diffusivities are collected in longer times.

A diffusion battery can be constructed as a series of individual diffusion collectors along the line of a cascade impactor. In this case a detector, usually a condensation nuclei counter, is used to measure the penetration through the battery. The smaller particles are collected in the first diffusion stage and the larger particles are not collected at all.

Smith et al.[34] describe a parallel diffusion battery where the flow rate is varied. The penetration

Table 17 Commercial Cascade Impactor Sampling Systems

Manufacturer	Name of Impactor	Substrates
Andersen 2000, Inc., P. O. Box 2076, Atlanta, GA 30320	Andersen Stack Sampler	Glass fiber
Meteorology Research, Inc., Box 637, Altadena, CA 91001	MRI Cascade Impactor	Stainless steel, grease, fiberglass, Mylar, and others
Pollution Control System Corp., 321 Evergreen Bldg., Renton, WA 98055	University of Washington	Stainless steel, fiberglass, grease
Sierra Instruments, Inc., P. O. Box 909, Village Square, Carmel Valley, CA 93924	Sierra Mod 226	Glass fiber
Zoltex Corp., 68 Worthington Dr., St. Louis, MO 63043	Brink	Glass fiber, aluminum, grease

for each flow rate is measured using a condensation nuclei counter. A curve of penetration versus physical diameter is shown in Figure 26.

Diffusion batteries are used in extractive sampling and generally require that the stack aerosol be diluted before sizing.

8.3.3 *Electrical Mobility Analyzer*

The electrical mobility analyzer developed by Liu et al.[38] operates by placing a known electrical charge on the particles and then measuring their mobility. The effective diameter range of the instrument is 0.03–1 μm.

9 ERROR ANALYSIS

9.1 Errors in Mass Sampling

Brooks[3] gives a complete analysis of the errors likely in mass sampling. He concluded that system accuracies of ±16% are possible with commercial state of the art mass trains and a 16-point traverse. In general the major contribution to the error is the mapping uncertainty associated with stratification in the sample plane.

The level of accuracy estimated by Brooks requires that all steps in the sampling be carried out with extreme care. State of the art equipment was defined as a mass train "which would consist of the highest accuracy components readily available commercially. For example it would include a high accuracy differential pressure transducer."

While 16% may be within the state of the art, most commercial mass trains do not, and indeed are not required to consist of the highest accuracy components available. Therefore, Brooks' estimate should be considered as the minimum error possible.

The error with a 16-point traverse with normal commercial mass sampling trains is probably about ±25%. The largest sources of error are due to deviations from isokinetic sampling, misalignment of the probe, mapping errors, and errors in measuring the gas velocity in the duct.

Table 18 lists most of the major sources of error in mass sampling.

In a field test, source variations probably introduce more uncertainty into the measurements than do the measurement techniques themselves.

Table 18 Sources of Measurement Errors for Mass

1. Errors due to probe
   a. Anisokinetic sampling velocity
   b. Probe not parallel to gas flow
   c. Dust collected on walls of probe or sample line
   d. Condensation in probe or sample line
2. Errors due to sample collector
   a. Efficiency less than 100%
   b. Condensation in collector
3. Errors in sample flow
   a. Meter inaccuracy
   b. Leaks
4. Errors in weighing
   a. Hygroscopic loss or regain of sample or filter media
   b. Loss of sample in handling
   c. Balance without adequate precision
5. Errors in integrating traverse
   a. Variations over time or space in dust load or gas velocity
   b. Integration error
   c. Too few traverse points
6. Errors due to personnel
   a. Reading and recording errors
   b. Failure to know and comply with requirements
   c. Calculation errors
7. Errors in data reduction
   a. Errors due to poor choice of data reduction method
   b. Calculation errors
   c. Not enough data

Table 19 Magnitude of Errors Associated with Impactors[35]

Parameter Affected	Source of Error	Magnitude of Error	Comments
d_{50}	Construction, tolerances of jets, secondary flow	Up to 50% for uncalibrated impactor especially for >5 μm	Laboratory calibration can reduce to less than 10%
D_{50}	Measurement of Q, T, P	Usually less than 10%	
Size distribution	Particle bounce	May be large from stage to stage	Sensitive to loading, substrates, and design
Size distribution and mass	Reactions of flue gas with substrates	Up to 100% or more, depending on gas and substrates	Minimize by proper substrate selection and use of blanks
Size distribution and mass concentration	Weighing errors	0.0–0.05 mg with properly used electrobalance	Can be checked in field; error in data depends on loading

9.2 Errors in Impactor Sampling

There are two questions that can be asked of cascade impactor data. The first is how well does the measured particle size distribution agree with the size distribution of the aerosol that was sampled. The second is how well does the measured particle size distribution agree with the particle size distribution of the whole flue gas particle mixture. The second question can be rephrased as how representative of the entire flue gas was the small gas stream that actually entered the cascade impactor.

The errors likely in the size distribution of the aerosol actually sampled are listed in Table 19.[35] In a well-conducted field program, the total error in the particle size distribution to all of these errors can be held to ±25%. This does not mean that the size distribution leaving a stack can be measured to ±25% because of errors in obtaining a representative sample of the flue gas.

If a single-point measurement is made the error due to stratification is usually ±50% and can be as high as several orders of magnitude. This means that the major source of error in well-conducted impactor sampling is due to stratification or mapping error, caused by too few traverse points. Therefore it is extremely important that the sampling points for cascade impactor measurements be carefully selected. In most situations the error due to stratification can be reduced to acceptable limits by sampling at two or three carefully selected points. At the outlet of a control device, where the concentration of large particles is low, it may be better to forget about isokinetic sampling and to conduct a multipoint traverse. If the deviations from isokinetic sampling are less than 30%, the error due to anisokinetic sampling will probably be acceptable. At the inlet of a control device, several runs should be conducted at various points across the duct.

The accuracy of the measured size distribution depends on the particle diameter range to be covered. If the particle diameter range is limited to aerodynamic diameters between 0.5 and 10 μmA, the particle size distribution for the entire flue gas can probably be defined within ±25% with a careful 2-point sampling program. If information on particles with diameters much larger than 10 μmA is desired, considerable sampling will be needed to define the size distribution within ±100%.

10 QUALITY ASSURANCE

As has been mentioned several times, particulate measurements are very difficult. Laboratory precision and care must be taken in very uncomfortable environments. Thus some form of quality assurance program is necessary to ensure that the proper care is taken. This quality assurance program must be designed and carried out with the same care that a quality assurance program for a precision laboratory would receive.

The first and most important part of the quality assurance program is to make sure that the people doing the field work know and understand the need for careful precise work. If they do, they will avoid many of the errors common in field programs. And that is what a good quality assurance program is all about—preventing the taking of bad data.

The quality assurance program should cover calibration of all equipment on some periodic schedule. EPA has established calibration requirements for all the equipment used in the EPA approved methods for stack sampling. Also equipment should be inspected before and after each use. If the equipment appears to be in less than top condition, it should be replaced or repaired and then recalibrated.

All substrates and filter materials for both mass and impactor sampling should be tested using blanks to ensure that there are no reactions between the flue gas and the substrate or filter. At least

one blank should be run during each day's testing. If there is a reaction, a different substrate or filter should be used.

A careful and complete log should be kept of everything that happens in the field. It should be possible to find out everything about the field test by reviewing the log. Strict accountability should be maintained to ensure that the log is maintained. The field supervisor should review the log at least daily.

Each run, including the blank runs, should have its own data sheet. The data sheet should follow the run as the filters or impactors move through the data reduction process. Again a strict chain of custody must be maintained. The data sheet should indicate when the run started, when it ended, and any important things that happened during the run. It should also show who the operators of the sampling equipment were.

The balance should be checked daily with a reference substrate to make sure that it is weighing correctly. Occasional blanks should be passed through the system to see what the weighing error may be. A small percentage of the filters and substrates should be reweighed as a weighing audit. The results of the audit should be checked daily so that corrective action can be taken. It does no good to find that the weighing was bad when the weighing audits are reviewed after you come out of the field.

Preliminary data reduction should be carried out in the field. The main objective of the preliminary data reduction is to make sure that the data appear reasonable. For example, if the preliminary data reduction shows that the inlet mass loading is less than the outlet mass loading, corrective action can be taken. If the error is not found until final data reduction back at the laboratory, the entire test may be of poor quality. The sooner a problem is found, the sooner it can be corrected. Take as much data as possible.

One of the most important features of a quality assurance program is to have written procedures for each operation. Everyone involved in the test should have a copy of the procedures and must understand them. The field supervisor has the responsibility for making sure that everyone has the procedures.

The check sheets in Figure 27 can be used to help in the quality assurance job.

General Administrative

Plant name _____ Date _____

Plant address _____

Source to be tested _____

Plant contact _____ Phone _____

Observers _____ Affiliation _____

_____ _____

_____ _____

_____ _____

Reviewed test program? _____ Comments _____

_____

Reviewed test program meeting notes? _____ Comments _____

_____

Reviewed correspondence? _____ Comments _____

_____

Test team company name _____ Phone _____

Supervisor's name _____ Address _____

Other members _____ Title _____

_____ _____

_____ _____

_____ _____

_____ _____

_____ _____

Fig. 27 Check sheet for quality assurance.[27]

General/Sampling Site

Stack/duct cross section dimensions _____ Equivalent diameter ____

Material of construction _____ Corroded? _____ Leaks? ___

Internal appearance: Corroded? _____ Caked particulate? _____ Thickness ___

Insulation? _____ Thickness _____ Lining? _____ Thickness ___

Nipple? _____ I.D. _____ Length _____ Flush with inside wall? _____

Straight run before ports _____ Diameters _____

Straight run after ports _____ Diameters _____

Photos taken? _____ Of what? _____

Drawing of sampling location:

Minimum information on drawing: stack/duct dimensions, location and description of major disturbances and all minor disturbances (dampers, transmissometers, etc.), and cross-sectional view showing dimensions and port locations.

General/Sampling System

Sampling method (e.g., EPA 5) _____

Sampling train schematic drawing:

Modifications to standard method _____

_____

Pump type: Fibervane with in-line oiler ___X___ Carbon vane ___X___ Diaphragm ___X___

Probe liner material _____ Heated? _____ Entire length? ____

Type "S" pitot tube: _____ Other _____

Pitot tube connected to: Inclined manometer _____ Or magnetic gauge _____

Range _____ Approx. scale length _____ Divisions _____

Orifice meter connected to: Inclined manometer _____ Or magnehelic gauge _____

Range _____ Approx. scale length _____ Divisions _____

Meter box brand ___X___ Sample box brand ___X___

Recent calibration of orifice meter-dry gas meter? _____ Pitot tubes? _____

Nozzles _____ Thermometers or thermocouples? _____ Magnehelic gauges? _____

Number of sampling points/traverse from Fed. Reg. _____ Number to be used _____

Length of sampling time/point desired _____ Time to be used _____

X—Not required by regulations

Train Assembly/Final Preparations **Run #** _____

(Use one sheet per run if necessary)

Filter holder clean before test? _____ Filter holder assembled _____

Correctly? _____ Filter media type _____ Filter clearly identified? _____

Filter intact? _____ Probe liner clean before test? _____

Nozzle clean? _____ Nozzle undamaged? _____

Impingers clean before test? _____ Impingers charged correctly? _____

Ball joints or screw joints? _____ Grease used? _____

Fig. 27 *(Continued)*

Kind of grease _____ Pitot tube tip undamaged? _____

Pitot lines checked for leaks? _____ Plugging? _____

Meter box leveled? _____ Pitot manometer zeroed? _____

Orifice manometer zeroed? _____ Probe markings correct? _____

Probe hot along entire length? _____ Filter compartment hot? _____

Temperature information available? _____ Impingers iced down? _____

Thermometer reading properly? _____ Barometric pressure measured? _____

If not, what is source of data? _____ $\Delta H@$ from most recent calibration _____

$\Delta H@$ from check against dry gas meter _____

Nomograph check:

If $\Delta H@ = 1.80$, $T_m = 100°F$, % $H_2O = 10\%$, $P_s/P_m = 1.00$, C = X (0.95)

If $C = 0.95$, $T_s = 200°F$, DN = 0.375, Δp reference = X (0.118)

Align $\Delta p = 1.0$ with $\Delta H = 10$; @ $\Delta p = 0.01$, ΔH = X (0.1)

For nomograph setup:

Estimated meter temperature X °F. Estimated value of P_s/P_m X

Estimated moisture content X %. How estimated? X

C factor X Estimated stack temperature X °F.

Desired nozzle diameter X

Stack thermometer checked against ambient temperature? _____

Leak test performed before start of sampling? _____ Rate _____ cfm @ _____ in. Hg.

Sampling (Use one sheet for each run if necessary) **Run #** _____

Probe-sample box movement technique:

Is nozzle sealed when probe is in stack with pump turned off? _____

Is care taken to avoid scraping nipple or stack wall? _____

Is an effective seal made around probe at port opening? _____

Is probe seal made without disturbing flow inside stack? _____

Is probe moved to each point at the proper time? _____

Is probe marking system adequate to properly locate each point? _____

Are nozzle and pitot tube kept parallel to stack wall at each point? _____

If probe is disconnected from filter holder with probe in the stack on a negative pressure source, how is particulate matter in the probe prevented from being sucked back into the stack?

_____

If filters are changed during a run, was any particulate lost? _____

Meter box operation:

Is data recorded in a permanent manner? _____ Are data sheets complete?

_____

Average time to reach isokinetic rate at each point _____

Is nomograph setting changed when stack temperature changes significantly? _____

Are velocity pressures (Δp) read and recorded accurately? _____

Is leak test performed at completion of run? _____ cfm @ _____ in. Hg.

General comment on sampling techniques _____

If Orsat analysis is done, was it: From stack? _____ From integrated bag? _____

Was bag system leak tested? _____ Was Orsat leak tested? _____

Check against air? _____

If data sheets cannot be copied, record: approximate stack temperature _____ °F

Nozzle dia. _____ in. Volume metered _____ acf

First 8 Δp readings _____ _____ _____ _____ _____ _____ _____ _____

Fig. 27 (*Continued*)

Sample Recovery

General environment-cleanup area _____

Wash bottle clean? _____ Brushes clean? _____ Brushes rusty? _____

Jars Clean? _____ Acetone grade _____ Residue on evap. spec. _____ %

Filter handled OK? _____ Probe handled OK? _____ Impingers handled OK? _____

After cleanup: Filter holder clean? _____ Probe liner clean? _____

Nozzle clean? _____ Impingers clean? _____ Blanks taken? _____

Description of collected particulate _____

Silica gel all pink? Run 1 _____ Run 2 _____ Run 3 _____

Jars adequately labeled? _____ Jars sealed tightly? _____

Liquid level marked on jars? _____ Jars locked up? _____

General comments on entire sampling project:

Observer's name _____ Title _____

Affiliation _____ Signature _____

Fig. 27 (*Continued*)[27]

11 DATA MANAGEMENT

In most field tests a large number of data sheets will be filled out. It is important that a data management system be worked out before the test begins. A single person should be responsible for checking all the data sheets for completeness at the end of each day. The same person should also be responsible for assembling all the data sheets into a single notebook.

A strict chain of custody of the data sheets should be established. The chain of custody must be enforced from the field tests through the time that the data sheets are filed in final storage after the report is written. A log book should be maintained to record who has the data when.

The sheet in Figure 28 can be used to help maintain the chain of custody.

12 COMPUTER PROGRAMS

The availability of small inexpensive microcomputers makes data reduction of particulate sampling data much easier than is possible by hand or even by a large computer. Denver Research Institute (DRI) has an excellent complete data reduction package for the TRS-80™ microcomputer.[28] This package includes graphic capability. The package is available from the National Technical Information Service or directly from DRI.

The computer programs presented here are very basic programs which will do all the necessary calculations for both mass train and impactor train sampling. The programs are written to ensure maximum portability between microcomputers and are designed for a minimal microcomputer system of cassette tape (although disk is highly recommended), minimum random access memory (RAM), and a line printer. For the most part the programs are straightforward translations of the various equations in the text. The only program that will be extensively commented on is the impactor data reduction program.

The programs are written in TRS-80 Model I Level II Basic. The use of special features of Level II Basic has been minimized to ensure that the programs can be used on other computers with minimum changes.

All of the programs accept data input in either English or metric units. The user must specify the type of units before beginning data entry. The units used for the various input data are given in the program.

To use the programs, simply provide the data asked for. Do not worry if you make a mistake entering data. You will be given a chance to review the data before the calculations begin.

Plant _____

Date sampled _____ Test number _____

Run number _____

Sample Recovery

Container Code	Description

Person engaged in sample recovery

Signature _____

Title _____

Location at which recovery was done _____

_____

Date and time of recovery _____

Sample(s) recipient, upon recovery if not recovery person

Signature _____

Title _____

Date and time of receipt _____

Sample storage _____

Laboratory person receiving sample

Signature _____

Title _____

Date and time of receipt _____

Sample storage _____

Analysis

Container code	Method of analysis	Date and time of analysis	Signature of analyst

Fig. 28 Check sheet for chain of custody.[27]

The impactor program is based on the TI-59 program presented by Sparks[30] and in part on the program in the DRI[25] package. The important feature of the program is that a spline fit is used to interpolate between data points and to differentiate the cumulative distribution curve to produce the $dm/d \log d$ distribution.

The spline fit gives the smoothest curve possible that passes through the data points. The curve is mathematically well defined. In general, the spline fit is the best way to differentiate sparse data. Before the spline is fit to the data, the cumulative distribution is transformed into log normal space. Sparks[30] has shown that use of the spline fit to data transformed into log normal space results in the smallest error in calculating penetration as a function of particle diameter as measured by cascade impactors. See Lawless[19] or Sparks[30] for details of the spline fit and the log normal transformation.

The use of the programs is best demonstrated by example problems given below.

Example 1: Calculation of Molecular Weight

Input data:
% CO = 1
% CO_2 = 16
% O_2 = 4
% N_2 = 79

Run program Orsat/BAS.
Answer: 30.72 g/g-mole.

Example 2: Fraction of Water Vapor in Gas

Input data:
Dry gas meter volume = 0.0283 m^3
Pressure at meter = 760 mm Hg
Temperature at meter = 30°C
Initial impinger volume = 10 ml
Final impinger volume = 12.5 ml

Run program MOIST/BAS.
Select metric units and input data.
Answer: Fraction water vapor in gas = 0.108707.

Example 3: Calculation of Stack Velocity and Flow Rate

Input data:
Pitot tube coefficient = 0.87
Dry molecular weight = 30.48 g/g-mole
Fraction water vapor = 0.1
Stack temperature = 150°C
Absolute stack pressure = 760 mm Hg
Average delta p = 111.484 mm H_2O

Run program VEL/BAS.
Select metric units and input data.
Answer: Gas velocity = 18.5608 m/sec
Flow rate = 4.64×10^9 DNcm/hr

Example 4: Calculation of Mass Concentration

Input data:
Volume of gas sampled = 2.830 m^3
Temperature at meter = 28°C
Pressure at meter = 760 mm Hg
Pressure drop across orifice = 111 mm H_2O
Sampling time = 100 min
Fraction of water in gas = 0.0245
Weight of particulate = 100 mg
Stack temperature = 150°C
Stack pressure = 750 mm Hg
Gas velocity in stack = 5 m/sec
Cross-sectional area of nozzle = 0.000126 m^2

Run program METH5/BAS.
Select metric units and input data.
Answer: Particle concentration = 0.0359 g/DNm^3
Percent of isokinetic = 110.20

Note that the program will inform you if the sampling rate is within the allowable range of 90 to 110% of isokinetic. (DNm^3 is dry normal cubic meters.)

Example 5: Calculation of Mass Efficiency

Input data:
Outlet mass concentration = 0.03 g/DNm^3
Inlet mass concentration = 3 g/DNm^3

Run program EFFIC/BAS.
Input data
Answer: Mass penetration = 0.01
Mass efficiency = 99%

ORSAT PROGRAM

```
10  REM ORSAT PROGRAM BY LES VERSION 1 0 FILE NAME ORSAT/BAS
20  REM WRITTEN IN TRS-80 MODEL I DISK BASIC
30  CLEAR 100:REM CLEAR STRING SPACE
40  CLS
50  INPUT"ENTER TEST ID";ID$
60  INPUT"ENTER REMARKS";R$
70  PRINT STRING$(63,"=") :REM PRINTS = ACROSS SCREEN
80  PRINT"ENTER DATA ASKED FOR. PRESS ENTER AFTER EACH DATA ENTRY"
90  PRINT STRING$(63,"=")
100  PRINT"ENTER PERCENT CO (";CO;")":
110  INPUT CO
120  PRINT"ENTER PERCENT CO2 (";C2;")":
130  INPUT C2
140  PRINT"ENTER PERCENT O2 (";O2;")":
150  INPUT O2
160  PRINT"ENTER PERCENT N2 (";N2;")":
170  INPUT N2
180  REM NOW CHECK TO SEE IF DATA ARE OK
190  CLS
200  PRINT"PERCENT CO ";CO
210  PRINT"PERCENT CO2 ";C2
220  PRINT "PERCENT O2 ";O2
230  PRINT "PERCENT N2 ";N2
240  PRINT STRING$(63,"=")
250  INPUT"ARE THESE CORRECT Y OR N ";Y$
260  IF LEFT$(Y$,1)="Y" THEN 280 ELSE IF LEFT$(Y$,1)<>"N" THEN
PRINT "ANSWER Y OR N PLEASE": GOTO 250
270  PRINT"PLEASE CORRECT DATA":FOR I=1 TO 100:NEXT I: GOTO 40
280  REM NOW CALCULATE DRY MOLECULAR WEIGHT
290  MW=.44*C2 + .32*O2 + .28*(N2+CO)
300  PRINT"DRY MOLECULAR WEIGHT IS ";MW
310  PRINT STRING$(63,"=")
320  INPUT"DO YOU WANT HARDCOPY Y OR N";Y$
330  IF Y$<>"Y" THEN END
340  LPRINT"TEST ID ";ID$
350  LPRINT"REMARKS ";R$
360  LPRINT" CO2 ";C2;" CO ";CO;" O2 ";O2;" N2 ";N2
370  LPRINT"DRY MOLECULAR WEIGHT IS ";MW
380  END
```

MOISTURE DETERMINATION PROGRAM

```
10  REM DETERMINATION OF MOISTURE IN STACK GASES
20  REM VERSION 1.0 BY LES FILE NAME MOIST/BAS
30  REM WRITTEN IN TRS-80 LEVEL II BASIC
40  CLEAR 100
50  CLS
60  PRINT STRING$(63,"=")
70  INPUT"ENTER TEST ID ";ID$
80  INPUT"ENTER REMARKS ";R$
90  PRINT"DETERMINATION OF MOISTURE IN STACK GASES"
100  INPUT"ENTER E FOR ENGLISH UNITS OR M FOR METRIC ";U$
110  IF U$="E" THEN U$="ENGLISH UNITS " ELSE IF U$<> "M" THEN
PRINT "ANSWER E OR M PLEASE":GOTO 100
120  IF U$="M" THEN U$="METRIC UNITS"
130  CLS
140  PRINT STRING$(63,"=")
150  PRINT"ENTER DATA ASKED FOR"
160  PRINT STRING$(63,"=")
170  PRINT"ENTER DRY GAS METER VOLUME (";VM;")":
180  INPUT VM
190  PRINT"ENTER TEMPERATURE AT THE METER (";TM;"):
200  INPUT TM
```

```
210  PRINT"ENTER PRESSURE AT THE METER (";PM;")";
220  INPUT PM
230  PRINT"ENTER INITIAL VOLUME OF IMPINGER CONTENTS ML
(";VI;")";
240  INPUT VI
250  PRINT"ENTER FINAL VOLUME OF IMPINGER CONTENTS ML
(";VF;")";
260  INPUT VF
270  CLS
280  PRINT STRING$(63,"=")
290  PRINT"CHECK DATA FOR CORRECTNESS"
300  PRINT U$
310  PRINT" DRY GAS METER VOLUME "TAB(40);VM
320  PRINT"PRESSURE AT METER "TAB(40);PM
330  PRINT"TEMPERATURE AT METER";TAB(40);TM
340  PRINT"INITIAL IMPINGER VOLUME ML";TAB(40);VI
350  PRINT"FINAL IMPINGER VOLUME ML";TAB(40);VF
360  Y$=""
370  INPUT"ARE THESE CORRECT Y OR N";Y$
380  Y$=LEFT$(Y$,1)
390  IF Y$="Y" THEN 420 ELSE IF Y$<>"N" THEN PRINT"ANSWER Y OR
N PLEASE ":GOTO 370
400  PRINT"REENTER INCORRECT DATA"
410  FOR J=1 TO 200:NEXT J:GOTO 110
420  REM DO THE CALCULATIONS
430  IF LEFT$(U$,1)="E" THEN TM=TM+460 ELSE TM=TM+273
440  IF LEFT$(U$,1)="E" THEN VW=.0474*(VF-VI) ELSE
VW=(VF-VI)/1000:REM CONVERT ML TO EITHER CUBIC FT OR CUBIC
METERS
450  IF LEFT$(U$,1)="E" THEN VE=17.71*VM*PM/TM ELSE VE=
VM*PM/760*293/TM
460  BW=VW/(VE+VW)+.025
470  CLS:PRINT:PRINT :PRINT STRING$(63,"=")
480  PRINT "FRACTION OF WATER IN GAS = ";BW
490  PRINT:PRINT STRING$(63,"=")
500  Y$=""
510  INPUT"DO YOU WANT HARDCOPY Y OR N";Y$
520  IF Y$<>"Y" THEN END ELSE PRINT"BE SURE PRINTER IS ON"
530  LPRINT"TEST ID ";ID$
540  LPRINT"REMARKS ";R$
550  LPRINT" VOLUME OF METER ";VM
560  LPRINT"TEMPERATURE OF METER ";TM;" PRESSURE OF METER ";PM
570  LPRINT"AMOUNT OF WATER COLLECTED ";VW
580  LPRINT"FRACTION OF WATER IN GAS ";BW
590  END
```

VELOCITY DETERMINATION PROGRAM

```
10  REM FILE NAME VEL/BAS
20  REM DETERMINATION OF STACK GAS VELOCITY AND FLOW RATE
30  REM TYPE S PITOT TUBE
40  REM VERSION 1.0 FOR TRS-80 MODEL I DISK BASIC
50  REM REQUIRES LEVEL II BASIC AND 16 K MINIMUM
60  CLEAR 100
70  CLS
80  PRINT STRING$(63,"=")
90  PRINT"DETERMINATION OF STACK GAS VELOCITY AND FLOW RATE"
100  PRINT STRING$(63,"=")
110  U$=""
120  INPUT"ENTER TEST ID";ID$
130  INPUT"ENTER REMARKS";R$
140  INPUT"ENTER E FOR ENGLISH UNITS OR M FOR METRIC UNITS";U$
150  IF U$="E" THEN KP=85.48:FL=-1:GOTO 180
160  IF U$<>"M" THEN PRINT"ANSWER E OR M PLEASE":GOTO 140
```

```
170  KP= 34.97     : FL=1
180  CLS
190  REM DATA INPUT
200  IF FL=-1 THEN F$="ENGLISH UNITS" ELSE F$="METRIC UNITS"
210  PRINT STRING$(63,"=")
220  PRINT"ENTER DATA ASKED FOR IN ";F$
230  PRINT STRING$(63,"=")
240  INPUT"PITOT TUBE COEFFICIENT ";CP
250  INPUT"ENTER DRY MOLECULAR WEIGHT ";MW
260  INPUT"FRACTION WATER VAPOR";BW
270  INPUT"ENTER STACK TEMPERATURE ";TS
280  INPUT"ENTER AVERAGE DELTA P ";DP
290  INPUT"ENTER STACK ABSOLUTE STACK PRESSURE ";PS
300  INPUT"ENTER CROSS SECTIONAL AREA OF STACK ";A
310  CLS
320  PRINT"REVIEW INPUT DATA FOR ERRORS"
330  PRINT STRING$(63,"=")
340  PRINT"PITOT TUBE COEFFICIENT ";CP
350  PRINT"DRY MOLECULAR WEIGHT ";MW
360  PRINT"FRACTION OF WATER VAPOR ";BW
370  PRINT"STACK TEMPERATURE ";TS
380  PRINT"AVERAGE DELTA P ";DP
390  PRINT"ABSOLUTE STACK PRESSURE ";PS
400  PRINT"CROSS SECTIONAL AREA OF STACK ";A
410  PRINT STRING$(63,"=")
420  Y$=""
430  INPUT"ARE THESE CORRECT Y OR N ";Y$
440  Y$=LEFT$(Y$,1)
450  IF Y$="Y" THEN 490 ELSE IF Y$<>"N" THEN PRINT "ANSWER Y
OR N PLEASE ":GOTO 430
460  PRINT"REENTER INCORRECT DATA ":FOR J=1 TO 200:NEXT J
470  CLS
480  GOTO 140
490  REM CALCULATE VELOCITY
500  IF FL=-1 THEN TS=TS+460 ELSE TS=TS+273
510  IF FL=-1 THEN TD=528 ELSE TD=293 :REM STANDARD
TEMPERATURE
520  IF FL=-1 THEN PD=29.92 ELSE PD=760
530  IF FL=-1 THEN V$="FPS" ELSE V$="MPS"
540  IF FL=-1 THEN Q$="DSCFH" ELSE Q$="DRY NORMAL CUBIC METER
PER HR"
550  MS=MW*(1-BW)+18*BW REM WET MOLECULAR WT
560  VS=KP*CP*DP[.5*(TS/PS/MS)[.4
570  QS=3600*(1-BW)*VS*A*(TD/TS)*(PS/PD)
580  CLS
590  PRINT STRING$(63,"=")
600  PRINT"STACK VELOCITY = ";VS;V$
610  PRINT"FLOW RATE = " ;QS;Q$
620  PRINT
630  PRINT STRING$(63,"=")
640  INPUT"DO YOU WANT HARDCOPY Y OR N"; Y$
650  IF Y$<>"Y" THEN END ELSE PRINT"BE SURE PRINTER IS ON"
660  LPRINT"TEST ID ";ID$
670  LPRINT"REMARKS ";R$
680  LPRINT"VELOCITY = ";VS;V$
690  LPRINT "FLOW RATE = ";QS;Q$
700  END
```

METHOD 5 PROGRAM

```
10  REM FILE NAME METH5/BAS
20  REM DETERMINATION OF PARTICULATE EMISSIONS
30  REM VERSION 1.0
40  REM WRITTEN IN TRS-80 LEVEL II BASIC BY LES
```

```
50  REM ****************************************
60  CLEAR 200
70  DIM F$(12),X(12)
80  F$(7)="WEIGHT OF PARTICULATE COLLECTED ####.### MG"
90  CLS
100  PRINT STRING$(63,"=")
110  PRINT"DETERMINATION OF PARTICULATE EMISSIONS"
120  INPUT"ENTER TEST ID ";ID$
130  INPUT"ENTER REMARKS ";R$
140  PRINT STRING$(63,"=")
150  INPUT"ENTER E FOR ENGLISH UNITS OR M FOR METRIC UNITS";U$
160  IF U$="E" THEN 740 ELSE IF U$="M" THEN 850 ELSE
PRINT"ANSWER E OR M PLEASE"
170  GOTO 150
180  REM NOW GET THE INFORMATION
190  F$(6)="FRACTION OF WATER VAPOR IN GAS #.####"
200  CLS
210  PRINT STRING$(63,"=")
220  FOR J=1 TO 11
230  PRINT USING F$(J);X(J);
240  INPUT X(J)
250  NEXT J
260  CLS
270  PRINT STRING$(63,"=")
280  PRINT"CHECK DATA FOR ERRORS"
290  PRINT STRING$(63,"=")
300  FOR J=1 TO 11
310  PRINT USING F$(J);X(J)
320  NEXT J
330  Y$=""
340  INPUT"ARE THESE CORRECT Y OR N";Y$
350  Y$=LEFT$(Y$,1)
360  IF Y$="Y" THEN 390 ELSE IF Y$<>"N" THEN PRINT"ANSWER Y OR
N PLEASE ";:GOTO 340
370  PRINT"REENTER INCORRECT DATA ";:FOR J=1 TO 200:NEXT J
380  GOTO 180
390  REM NOW CALCULATE IT
400  REM FIRST CALCULATE METER FLOW AT STANDARD DRY CONDITIONS
410  IF LEFT$(U$,1)="E" THEN M=17.64 ELSE M=0.3858
420  VD=X(1)*M*(X(3)+X(4)/13.6)
430  TM=X(2)
440  IF LEFT$(U$,1)="E" THEN TM=TM+460 ELSE TM=TM+273
450  VD=VD/TM
460  IF LEFT$(U$,1)="E" THEN K1=0.0154 ELSE K1=.001
470  IF LEFT$(U$,1)="E" THEN C$="GR/DSCF" ELSE C$="G/DN CUBIC
METER"
480  C=K1/VD*X(7)
490  CLS
500  PRINT STRING$(63,"=")
510  C$="PARTICLE CONCENTRATION ###.#### "+C$
520  PRINT USING C$;C
530  PRINT STRING$(63,"=")
540  REM NOW CALCULATE % ISOKINETIC
550  IF LEFT$(U$,1)="E" THEN K4=0.0945 ELSE K4=4.320
560  IF LEFT$(U$,1)="E" THEN TS=X(8)+460 ELSE TS=X(8)+273
570  I=K4*TS*VD/(X(9)*X(10)*X(11)*X(5)*(1-X(6)))
580  IF I>110 OR I<90 THEN Z$="ISOKINETIC RATE OUT OF RANGE"
ELSE Z$="ISOKINETIC RATE IN RANGE"
590  PRINT USING"PERCENT OF ISOKINETIC ####.#### ";I
600  PRINT Z$
610  Y$=""
620  INPUT"DO YOU WANT HARDCOPY Y OR N";Y$
630  IF Y$<>"Y" THEN END ELSE PRINT"BE SURE PRINTER IS ON"
640  LPRINT"TEST ID ";ID$
650  LPRINT"REMARKS ";R$
```

```
660  LPRINT"INPUT DATA"
670  FOR J=1 TO 11
680  LPRINT USING F$(J);X(J)
690  NEXT J
700  LPRINT USING C$;C
710  LPRINT USING"PERCENT OF ISOKINETIC ####.## ";I
720  LPRINT Z$
730  END
740  REM SET UP FOR INPUT
750  F$(1)="VOLUME OF GAS THROUGH GAS METER ####.## CUBIC
FEET"
760  F$(2)="TEMPERATURE AT THE METER ####.## DEG F"
770  F$(3)="PRESSURE AT THE METER ####.## INCHES HG"
780  F$(5)="SAMPLING TIME ####.## MINUTES"
790  F$(4)="PRESSURE DROP ACROSS THE ORIFICE ##.### INCHES
WATER"
800  F$(8)="STACK TEMPERATURE ####.## DEG F"
810  F$(9)="STACK PRESSURE ####.## INCHES HG"
820  F$(10)="GAS VELOCITY IN STACK #### ### FT/S"
830  F$(11)="CROSS SECTIONAL AREA OF NOZZLE ###.##### SQUARE
FT"
840  GOTO 180
850  REM SET UP FOR METRIC DATA ENTRY
860  F$(1)="VOLUME OF GAS SAMPLED #### ### CUBIC METERS"
870  F$(2)="TEMPERATURE AT THE METER ###.## DEG C"
880  F$(3)="PRESSURE AT THE METER ####.## MM HG"
890  F$(4)="PRESSURE DROP ACROSS THE ORIFICE ###.### MM WATER"
900  F$(5)="SAMPLING TIME #### ## MINUTES"
910  F$(8)="STACK TEMPERATURE ####.## DEG C"
920  F$(9)="STACK PRESSURE ####.## MM HG"
930  F$(10)="GAS VELOCITY IN STACK ####.### M/S"
940  F$(11)="CROSS SECTIONAL AREA OF NOZZLE ##.###### SQUARE
METERS"
950  GOTO 180
```

EFFICIENCY PROGRAM

```
10  REM FILE NAME EFFIC/BAS
20  REM CALCULATE MASS EFFICIENCY
30  REM FOR TRS-80 LEVEL II BASIC BY LES
40  CLEAR 100
50  CLS
60  PRINT STRING$(63,"=")
70  PRINT"MASS EFFICIENCY CALCULATION"
80  INPUT"ENTER RUN ID ";ID$
90  INPUT"ENTER REMARKS ";R$
100  INPUT"ENTER OUTLET MASS CONCENTRATION ";CO
110  INPUT"ENTER INLET MASS CONCENTRATION ";CI
120  CLS
130  PRINT STRING$(63,"=")
140  PRINT USING"OVERALL PENETRATION = ###.#### ";CO/CI
150  PRINT USING"OVERALL EFFICIENCY = ###.##### %
";(1-CO/CI)*100
160  Y$=""
170  INPUT"DO YOU WANT HARDCOPY Y OR N";Y$
180  IF Y$<>"Y" THEN END ELSE PRINT"BE SURE PRINTER IS ON"
190  LPRINT"TEST ID ";ID$
200  LPRINT"REMARKS ";R$
210  LPRINT"INLET MASS CONCENTRATION ";CI
220  LPRINT"OUTLET MASS CONCENTRATION ";CO
230  LPRINT USING"OVERALL MASS PENETRATION = ##.####### ";CO/CI
240  LPRINT USING"OVERALL MASS COLLECTION EFFICIENCY =
###.##### ";(1-CO/CI)*100
250  END
```

REFERENCES

1. EPA, Standards of Performance for New Sources: Revision to Reference Methods 1–8, *Federal Register* 42(160), 41776–41782 (1977).
2. Smith, W. B., Cushing, K. M., and McCain, J. D., *Particulate Sizing Techniques for Control Device Evaluation*, EPA Report EPA-650/2-74-102, Oct. 1974.
3. Brooks, E. F., *Total Particulate Mass Emission Sampling Errors*, Report for EPA Contract 68-02-2165, Task 26, Research Triangle Park, NC, not published.
4. Stairmand, C. J., *Trans. Instn. Chem. Engrs.* 29, 15 (1951).
5. Davies, C. N., *Dust is Dangerous*, Faber and Faber, London, 1954.
6. EPA, Method 17 Determination of Particulate Emissions from Stationary Source (In-Stack Filtration Method), *Federal Register* 43(37), 7584–7596 (1978).
7. Sparks, L. E., Importance of Particle Size Distribution, *Proc. Second Symposium of Particulate Control Technology*, EPA Report EPA-600/9-80-639, 1980.
8. Rabe, O. G., Aerosol Aerodynamic Size Conventions for Inertial Sampler Calibration, *J. Air Poll. Control Assoc.* 9, 856 (1976).
9. McCain, J. D., and McCormack, Non-ideal Behavior in Cascade Impactors, in *Proc. Advances in Particle Sampling and Measurement (Daytona Beach, FL, October 1979)*, EPA Report EPA-600/9-80-004, Jan. 1980.
10. Cushing, K. M., Lacy, G. E., McCain, J. D., and Smith, W. B., *Particulate Sizing Techniques for Control Device Evaluation: Cascade Impactor Calibrations*, EPA Report EPA-600/2-76-280, Oct. 1976.
11. Esmen, N. A., and Lee, T. C., Distortion of Cascade Impactor Measured Size Distribution Due to Bounce and Blow Off, *American Industrial Hygiene Assoc. J.* 41, 410 (1980).
12. Gooch, J. P., Marchant, G. H., Jr., and Felix, L. G., *Particulate Collection Efficiency Measurements on an ESP Installed on a Coal Fired Boiler*, EPA Report EPA-600/2-77-011, Jan. 1977.
13. Calvert, S., Lake, C., and Parker, R., *Cascade Impactor Calibration Guidelines*, EPA Report EPA-600/2-76-118, 1976.
14. Harris, D. B., *Procedures for Cascade Impactor Calibration and Operation in Process Streams*, EPA Report EPA-600/2-777-004, Jan. 1977.
15. Smith, W. B., Cushing, K. M., and McCain, J. D., *Procedures Manual for Electrostatic Precipitator Evaluation*, EPA Report EPA-600/7-77-059, June 1977.
16. Idem, *Particulate Sizing Techniques for Control Device Evaluation*, EPA Report EPA 650/2-74-102, October 1974.
17. Lundgren, D. A., and Balfour, D., *Use and Limitations of In-Stack Impactors*, EPA Report EPA-600/2-80-048, Feb. 1980.
18. Ensor, D. S., personal communication, 1981.
19. Lawless, P. A., *Analysis of Cascade Impactor Data for Calculating Particle Penetration*, EPA Report EPA-600/7-78-189, September 1978.
20. Sparks, L. E., *Cascade Impactor Data Reduction with the SR-52 and TI-59 Programmable Calculators*, EPA Report EPA-600/7-78-226, Nov. 1978.
21. Johnson, J. W., Clinard, G. I., Felix, L. G., and McCain, J. D., *A Computer Based Impactor Data Reduction System*, EPA Report EPA-600/7-78-042, 1978.
22. Wasmundt, K. C., and Tegtmeyer, S., *TRS-80 Cascade Impactor Data Reduction System*, Electronic Division, Denver Research Institute, Denver, Colo., March 1980.
23. Smith, W. B., and Wilson, R. R., Jr., *Development and Laboratory Evaluation of a Five-Stage Cyclone System*, EPA-600/7-78-008, 1978.
24. Wilson, R. R., Jr., Cavanaugh, P. R., Cushing, K. M., Farthing, W. E., and Smith, W. B., *Guidelines for Particulate Sampling in Gaseous Effluents from Industrial Processes*, EPA-600/7-79-028, 1979.
25. Liu, B. Y. H., Whitby, K. T., and Pui, D. Y. H., A Portable Electrical Analyzer for Size Distribution Measurement of Sub-Micron Aerosols, *J. Air Pollut. Control Assoc.* 24, 1067 (1974).
26. Ensor, D. S., personal communication, 1980.
27. U. S. Environmental Protection Agency, *Handbook Industrial Guide for Air Pollution Control*, EPA-625/6-78-004, 1978.
28. Smith, W. B., and McCain, J. D., Particle Size Measurement in Industrial Flue Gases, in *Air Pollution Control, Part III* (W. Strauss, ed.), Wiley, New York, 1972. (Much of the data in the various EPA reports are covered here.)
29. Fuchs, N. A., *The Mechanics of Aerosols*, Pergamon Press, New York, 1964.

Note that all of the EPA reports are available from the National Technical Information Service, Springfield, VA.